Particle Physics for Non-Physicists— A Tour of the Microcosmos

Part I

Professor Steven Pollock

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Steven Pollock, Ph.D.

Associate Professor of Physics, University of Colorado, Boulder

Steven Pollock is associate professor of physics at the University of Colorado, Boulder. He did his undergraduate work at MIT, receiving a B.Sc. in physics in 1982. He holds a Master's and a Ph.D. in physics from Stanford University, where he completed a thesis on "Electroweak Interactions in the Nuclear Domain" in 1987. Professor Pollock did postdoctoral research at NIKHEF-K (the National Institute for Nuclear and High Energy Physics) in Amsterdam, Netherlands, from 1988–1990 and at the Institute for Nuclear Theory in Seattle from 1990–1992. He spent a year as senior researcher at NIKHEF in 1993 before moving to Boulder.

Professor Pollock's research work is on the intersections of nuclear and particle physics, with special focus on parity violation, neutrino physics, and virtual strangeness content of ordinary matter. Professor Pollock was a teaching assistant and tutor for undergraduates throughout his years as both an undergraduate and graduate student. As a college professor, he has taught a wide variety of university courses at all levels, from introductory physics to advanced nuclear and particle physics, including quantum physics (both introductory and senior level) and mathematical physics, with an intriguing recent foray into the physics of energy and the environment. Professor Pollock is author of *Thinkwell's Physics I*, a CD-based "next-generation" multimedia textbook in introductory physics.

Professor Pollock became a Pew/Carnegie National Teaching Scholar in 2001 and is currently pursuing classroom research into student attitudes toward physics in large-lecture introductory courses. He received an Alfred P. Sloan Research Fellowship in 1994 and the Boulder Faculty Assembly (CU campus-wide) Teaching Excellence Award in 1998. He has presented both nuclear physics research and his scholarship on teaching at numerous conferences, seminars, and colloquia. Professor Pollock is a member of the American Physical Society, Nuclear Physics Division, and the American Association of Physics Teachers.

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Particle Physics for Non-Physicists—
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Scope:

The buzzwords appear with regularity in newspapers and magazines**—***quarks*, *neutrinos*, the *Higgs boson*, *superstrings*... It's the lingo of particle physics, the study of the deepest, most fundamental constituents and interactions of the physical world. This course will offer a tour of the particle zoo and the ideas and phenomena involved in qualitatively understanding current concepts of modern physics. No math involved! What's so strange about strange quarks? Why didn't we build a superconducting supercollider? Should we believe in particles that no one has ever seen—and never will? We'll learn about the most fundamental constituents of nature and the forces they feel—the history and discoveries, the apparatus and ideas, some of the curious characters involved, and the research and mysteries that are still being pursued today.

We begin on a fairly historical track. From the ancient Greek philosophers, we jump to Renaissance scientists whose work formed the starting point of physics. The scientific method developed by Isaac Newton more than 300 years ago continues to serve us well. Many of the physical insights Newton had, although now deepened and improved by modern physics ideas, are still relevant for understanding how the world works, which is the goal of this course and, indeed, of all physics. We jump again, to the start of the twentieth century, when new discoveries forced a radical shift in thinking about the behavior of matter—the dawn of quantum mechanics. We will not cover (or assume) any detailed knowledge of these laws of physics, discussing only the key ideas we need for the rest of this course. A "classical" approach to particle physics, although not technically correct, will serve us quite well. Students will find that understanding the basic elements of particle physics using common sense and classical intuition is possible, provided that we keep our minds open for the occasional quantum weirdness!

We will follow the early developments, both theoretical and experimental, and see how they lead us to an organizing scheme for matter at the smallest possible scale. The idea of seeking the fundamental constituents and the forces they feel will guide us through the rest of the course. We will learn about the growing "particle zoo," with just enough vocabulary to talk sensibly about the fundamental objects discovered from the early 1900s up through the most recent findings. This will lead us to quarks and neutrinos, force carriers and Higgs bosons, squarks and Zinos. Along the way, we will learn qualitatively about the theories required to describe such creatures—quantum fields, virtual particles, and all!

All this leads to what is now known as the *standard model of particle physics*—really the standard *theory*—a complete and self-consistent description of the apparently fundamental, point-like building blocks of everything, their interactions with one another, and the "rules of the game." We then move to more modern questions: Do we really have a fundamental theory at hand? Does that question even make sense? What is going on today in the world of particle physics? What are the central issues? What's hot these days? As we move through the course we will continually ask ourselves two key questions: Why is this idea interesting, and how do I know that it is true? Both are at the heart of appreciating science.

Lecture One

The Nature of Physics

Scope: What is the world made of? How do the constituents "fit together"? What are the fundamental rules that these constituents obey? These are the broad and deep questions addressed by the branch of science called particle physics. We will begin with a discussion of the history and development of human understanding of atoms and "subatoms." We will articulate some of the primary current ideas in particle physics. A central theme will be the idea of *reductionism* in science, which leads to the concept of simplicity as a guiding principle in seeking truths about nature. We will discuss the broad relevance of particle physics to science, and to our lives, asking the key question (as we will throughout the course) "Why should we care about this?"

What background do you need to know to follow this course? Very little—mostly just some curiosity and common sense. The content will be entirely nonmathematical, but we needn't be afraid of introducing the occasional number when it helps our understanding.

> People are always asking for the latest developments in the unification of this theory with that theory, and they don't give us a chance to tell them anything about one of the theories that we know pretty well. They always want to know things that we don't know. So, rather than confound you with a lot of half-cooked, partially analyzed theories, I would like to tell you about a subject that has been very thoroughly analyzed. I love this area of physics and I think it's wonderful…
>
> —Richard Feynman (*QED: The Strange Theory of Light and Matter*, chapter 1)

Outline

I. Physics as a whole is the study of what the world is made of, how it works, and why things in the world behave the way they do.

- **A.** Particle physics is the branch of physics that tries to understand the world at its smallest level—the simplest building blocks of the world and the most fundamental rules that govern how things work.
- **B.** The concerns of particle physics can be summed up in five words that address questions specific to this field:
  1. *Force* and *energy*: How and why do things interact?
  2. *Matter*: What is the world made of? What are these things that are interacting?
  3. *Space* and *time*: What is the framework in which these things exist and interact?
- **C.** The physical world seems very complicated; it contains many types of objects and exhibits many types of phenomena, but these can be tied together. Particle physics shows that everything physical arises from a simple set of building blocks and rules.

II. What is the world made of? Greek natural philosophers from about 400 B.C. debated this question.

- **A.** Democritus put forth the idea that everything in the world was made of little "chunks," which he called *atomos*, meaning "unbreakable" or "uncuttable."
  1. To illustrate this idea, think of a stick of butter. It is a physical object that has certain characteristics: It is yellow, soft, and so on. If you cut the stick of butter in half, you still have butter. You haven't changed its essence; you just have less butter.
  2. Democritus believed that if you kept cutting the butter in half, again and again, you would ultimately find a physical and real but uncuttable chunk. In other words, matter is not infinitely divisible.
- **B.** Aristotle disagreed with this idea.
  1. For Aristotle, the world was made up of the four elements: earth, air, fire, and water.
  2. These elements are not physical chunks. They are characteristics or qualities, which means that they are infinitely divisible.
- **C.** Aristotle's view prevailed for millennia but has been discredited now.
  1. Neither of these philosophers was a scientist in the modern sense. They believed that the world could be understood by just thinking about it, not by collecting data.

2. The puzzle of how the world works was unsolved for a long time. Now, although it may seem arrogant to say so, this puzzle is largely solved. For example, we have physical evidence that the world is made of atoms, and we have physical evidence of subatomic particles, even smaller constituents of atoms.

D. The ancient Greek philosophers also asked themselves about the earth's place in the universe: Is the earth flat or is it a ball? Is the earth at the center of the universe or is something else at the center? It was not until 2000 years later, during the Renaissance, that thinkers began to collect data from nature to answer these questions.

1. Now that we have evidence about the solar system, we have developed a framework, or mental model, that allows us to understand certain phenomena.
2. Our goal in this course is to develop a similar mental model of particle physics.

III. One of the guiding principles of physics is *reductionism*.

A. Reductionism means "understanding" complex physical systems in terms of their constituents: what they are made of.

1. A doctor might "explain" the human body by saying that it is a collection of organs that are fairly universal and that function in certain ways. In other words, the doctor "reduces" a complex system to its fundamental building blocks.
2. A particle physicist tends to think even more reductively. When thinking about the human body, a physicist might ask, "What is a heart?" The answer is that it is a structure made of cells of a certain type that interact in well-defined ways. Again, a complicated system is understood by reducing it to its components and how they interact.
3. We can reduce the complexity even further by asking, "What is a cell? How does it work? What is a cell made of?" As we answer these questions, we ultimately arrive at universal components, atoms, which are constituents of everything in the world.

B. Particle physicists ask how far the complex system of the world can be reduced.

C. Reductionism is one approach to studying phenomena, but it is not the only approach, nor is it applicable to every field of human endeavor.

IV. Why should we study particle physics?

A. Often, when people ask this question, they are looking for technological applications.

1. Physics offers those applications in the form of televisions, microwave ovens, cell phones, and many other innovations.
2. Particle physics is responsible for the development of particle beam cancer therapy, superconducting magnets, PET scans, relativity corrections in global positioning satellites, and so on.
3. These applications are fascinating, but they are not the primary reasons for studying particle physics.

B. Particle physics also offers connections to other branches of science. We understand chemistry and, by extension, biology, astronomy, and cosmology, in part through the ideas of physics. No idea in science is independent of others.

C. Another reason to study particle physics is the innate human desire to know.

1. Particle physics is fundamental science; it looks at what's at the bottom. Almost any chain of "why" questions in science leads to the particles and interactions that build the world.
2. Our appreciation of the world is also enhanced by understanding its ultimate physical nature, its simplicity, regularity, and interconnectedness.

D. What is the role of particle physics in the broader world of science?

1. Particle physics is, in many respects, the most fundamental science there is. Although abstract, the ideas are elegant, simple, and compelling.
2. By no means has particle physics developed a complete description of the world. As mentioned earlier, however, physicists have built up a fairly deep understanding of the world, which is called the *standard model of particle physics*.

V. Where are we headed in this course?

A. Without getting heavily into mathematics, we will create a conceptual model of particle physics that we can then apply to understanding other aspects of our lives and the world around us.

B. We will use a quasi-historical approach that will evolve into a more conceptual one.

C. No background in physics is required for this course. We will learn what the world is made of, how the fundamental objects fit together, and what the big concepts are to arrive at the standard model of particle physics.

Essential Reading:

Kane, *The Particle Garden*, chapter I.

Weinberg, *Dreams of a Final Theory*, chapter III. (Long but "breezy." You may want to start at the beginning of this book because chapters I and II are listed for the next two lectures.)

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 1 (short).

Recommended Reading:

Lederman, *The God Particle*, chapter 2. (See comments on Weinberg's book above.)

Wilczek and Devine, *Longing for the Harmonies*, Prelude Two.

Questions to Consider:

1. How do you *know* the earth is round? Why do you believe that? What evidence can you think of that might convince a nonbeliever?
2. What is more important to you, the practical applications of science or the aesthetic and philosophical pleasure of learning "truths" about the world?
3. Does science in fact find truths, or are we merely making successively improved approximations? Or, to go to an extreme, could scientific truth be merely social construct?

Lecture Two

The Standard Model of Particle Physics

Scope: We begin by “zooming in” to the micro-world with a discussion of the distance scales involved. Where do we stand today in our understanding of the smallest building blocks of the world? The standard model of particle physics is one of the greatest quantitative success stories in science. What are the players; what are the forces; what are some of the concepts and buzzwords? This lecture begins our exploration of these questions and offers some teasers for what’s to come in the course. In what sense can or should we think of particle physics as “fundamental”?

> The fact that, at least indirectly, one can actually see a single elementary particle—in a cloud chamber, say, or a bubble chamber—supports the view that the smallest units of matter are real physical objects, existing in the same sense that stones or flowers do.
>
> —Werner Heisenberg, in an uncharacteristic quote (*The Physicist’s Conception of Nature*)

> Artists, like physicists, may not always be able to make themselves understood by the general public, but esotericism for its own sake is just silly.
>
> —Steven Weinberg (*Dreams of a Final Theory*)

Outline

I. The first step in our construction of the standard model of particle physics is to develop a sense of the *distance scales* of physics.

A. The central idea of particle physics is that all objects in the physical world can be understood to be constructed from a small underlying set of particles, interacting via a small, well-understood set of forces.

1. We need some frame of reference for the small scale of particle physics in relation to the ordinary world.
2. Picture a meter stick, which is similar to a yardstick, in your mind. A meter stick is usually divided into a thousand little lines that represent millimeters. That distance, 1/1000 of a meter, is about the smallest distance that people can easily visualize.
3. To describe such measurements, scientists usually use a system of scientific notation, in which 100, for example, is described as 10^2, or 10×10. This notation is a shorthand for describing very large and very small numbers.
4. Under this system, 1000 is 10^3, or $10\times10\times10$, or in metric terms, a kilo. A millimeter is 10^{-3}. The minus sign means $1 \div 1000$, or .001.
5. If we wanted to talk about 1/1000 of a millimeter, which itself is 1/1000 of a meter, that measurement would be one-millionth of a meter, or a micrometer, abbreviated as the term *micron*, or 10^{-6} meters.
6. A micron is hard to visualize, but if you looked through a good microscope, you might see a bacterium or a cell that is about a micron in size.
7. What if we shrink down by another factor of 1000? This measurement would be a billionth of a meter, or 10^{-9} meters. The metric prefix for this measurement is *nano*, and a nanometer is currently about the smallest distance scale that human beings can manipulate in technological devices.
8. If we shrink down by a factor of 10, not 1000, but just 1/10 of a nanometer, or 10^{-10} meters, that measurement is about the size of an atom, and all atoms are about the same size. This measurement is sometimes called an *angstrom*.
9. One way to visualize the size of an atom is to go through all these steps, as we have done. Another way to visualize this size is to think of an apple and the following analogy: An atom is to an apple as the apple is to the planet earth, also a factor of about 10^{10}.
10. We will look inside the atom and compare distance scales in the subatomic world to this distance scale of 10^{-10}m.

B. How else do we think of an atom? We might think of its “logo,” or the image of an atom that began to appear in textbooks in the 1950s.

1. This image shows a dot in the middle with about a half dozen other dots whizzing around it in elliptical orbits.
2. This is a primitive representation of what an atom is made of: a nucleus in the middle and the electrons orbiting around it, in orbits of about 10^{-10} meters in diameter.
3. This is not necessarily the correct way to think of atoms, but it is an adequate representation. It doesn't show all the subtleties of quantum mechanics, but it is a good concrete mental image that will work for our purposes.

II. How do we understand this mini–solar system?

A. First, we might ask, "Why don't the electrons simply fly off?" The answer is: simple electrical attraction, the same kind of attraction that is created when you rub a balloon on your shirt and stick it to the wall. Electrostatic forces hold things together when they are electrically charged.

1. The electron is negatively charged; the nucleus is positively charged.
2. Positive and negative electric charges attract each other, and that's what holds the atom together.

B. Next we might ask, "What is the nucleus?"

1. In the "logo," it is usually shown as a blob made up of smaller blobs, which are protons and neutrons.
2. Protons are positively charged objects. The neutrons are similar to the protons, but they are electrically neutral.
3. The protons and neutrons bundle together to form the nucleus.
4. What is the size of the nucleus? Typically, 10^{-14} meters, or 10,000 times smaller than the atom itself.
5. To visualize this system another way, picture a football field. The electrons are out in the end zones. In the middle of the field is a grape—that's the size of the nucleus.
   - **a.** If you can visualize this, then you begin to get a sense that an atom is mostly empty space. Even hard, solid objects are mostly empty space.
   - **b.** Electrons are far away from the middle and sense the presence of other electrons. Most of chemistry—most of the everyday world that we live in—arises from the interactions of electrons in one atom with electrons in another atom.

C. What holds the protons and neutrons together?

1. Protons and neutrons stick together by a very strong force that is not electrical. Electricity would actually make them fly apart, because like charges repel each other.
2. This force is called the *strong force*. It sticks the protons and neutrons together like pieces of Velcro. The strong force, or nuclear force, is responsible for nuclear energy and the powering of the sun.

D. The *standard model of particle physics* is the name for the framework in which we understand these particles and the forces by which they interact.

1. The standard model has built into it a set of fundamental particles. Electrons belong to that set of particles, but protons and neutrons do not.
2. If we were to zoom even further into the atom, down to the proton, which is 10^{-15} meters, we would find three tiny objects called *quarks* in very tight orbits around one another.

III. In the next lecture, we will begin to look at the evolution of ideas in classical physics.

A. Classical ideas arise from everyday phenomena, such as tossing a ball, riding a bike, and so on.

1. These experiences lead us to an understanding of our world, the construction of the laws of physics, that is very accurate. This understanding is also accurate in describing the micron-sized world and the nano-sized world.
2. However, as we begin to approach the distance scale of the atom, we see that these laws of physics are no longer completely accurate in describing the world.
3. We need to construct a new set of laws that describes the behavior of elements in this distance scale. These laws go by the names of *quantum mechanics* and *relativity*.

B. We will work our way quickly through the scientific ideas of the 1600s–1800s, then begin to focus on the evolution of ideas in the twentieth century.

C. Along the way, we will need some vocabulary, particularly the terms *quark*, *lepton*, and *force carrier*.

1. Quarks are very heavy objects with, as far as we know, no internal structure. Quarks also interact very strongly; they bind together incredibly tightly to form the nucleus of atoms. With the quark, we may be looking at a bottom-most layer of the world.

2. Leptons are a class of particles; the electron is the most familiar of these. Other leptons are the neutrinos and muons.
3. The idea of a force carrier is a modern way of thinking about interactions between particles through yet another particle. Thus, a photon is the force carrier of electricity and magnetism. A gluon is the carrier of the very strong force that binds the quarks together.

D. Our name for what we will study in this course is *relativistic quantum field theory*.
1. *Relativistic* comes from Einstein's theory of relativity.
2. *Quantum* is the word for the evolution in our way of thinking from the classical ideas about how objects push and pull against one another. Those classical ideas are modified when the objects are really tiny.
3. *Field* refers to force fields, a way of thinking about electric, magnetic, or nuclear forces in the world.

E. In our next lecture, we begin to look at the development of the ideas of classical physics and the causes of the transition to quantum physics.

Essential Reading:

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapters 2.1–2.2 (up to p. 18) and 2.9.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 2.

Weinberg, *Dreams of a Final Theory*, chapter I.

Recommended Reading:

Lederman, *The God Particle*, chapter 1.

Calle, *Superstrings and Other Things*, chapter 1.

Questions to Consider:

1. What do you think is the smallest object you could see directly with unaided eyes? What limits your ability to literally see something smaller than that?
2. To what extent can physicists ever prove a theory? Is it proven that the sun will rise tomorrow? Is your confidence that the sun will rise tomorrow improved or unaffected by your awareness of a simple explanatory model of the solar system (round, rotating earth orbiting the sun)?
3. Consider these two statements: The sun will still rise every day next year. The sun will still rise every day 20 billion years from now. What affects your confidence in the truth of the two statements?

Lecture Three

The Prehistory of Particle Physics

Scope: Our story began with the Greek philosophers, but we move quickly to the origins of contemporary science in the 1600s. We summarize some aspects of the scientific evolution of atomism, starting with pre-scientific ideas, then the "classical" worldview formed by Isaac Newton, to the modern ideas of "fundamental constituents." We examine some specific details leading to our understanding of atoms, such as the periodic table, the origins of chemistry, and early questions about the existence and utility of atoms. We conclude with a survey of the state of physics knowledge at the start of the 1900s. How could a famous physicist say that physics was "done" in 1899?

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms. Little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.
>
> —Richard Feynman (*The Feynman Lectures in Physics*, chapter 1, volume 1)

> So, naturalists observe, a flea
> Has smaller fleas that on him prey;
> And these have smaller still to bite 'em;
> And so proceed ad infinitum.
>
> —Jonathan Swift ("Poetry, a Rhapsody")

Outline

I. Particle physics is twentieth-century science, but to understand it, we must look into the "prehistory" of science.

II. How do we know that atoms exist?

- **A.** As Feynman notes in the quote that introduces this lecture, once we appreciate the idea of atoms, we begin to understand a wealth of data and concepts about how the world works.
- **B.** As mentioned in Lecture One, Greek philosophers debated the existence of the atom 2500 years ago. The Greeks were not scientists, however; they were philosophers. In the 1700s and 1800s, science began to develop an approach in which questions were asked of the world, rather than posed among philosophers.
- **C.** This approach is the scientific method. We propose a hypothesis, then we try to determine the quantitative consequences of that hypothesis by testing it in the lab.
- **D.** With regards to atoms, that testing began in the 1800s with chemistry.
  - **1.** John Dalton, the father of chemistry, began to realize that there is a great deal of order and regularity in what happens when you start combining chemicals.
  - **2.** In particular, Dalton made careful measurements of weights of elements. For example, he found that if carbon monoxide is heated, it will always break down into the same ratio of carbon and oxygen, that is, 12 parts carbon to 16 parts oxygen.
  - **3.** Dalton began experimenting with many different materials and realized that he could isolate and understand these elements based on their masses. Even though he didn't know what the unit of mass was, he understood chemistry as a combination and reorganization of these fundamental, unbreakable units.
  - **4.** Once the processes of chemistry began to be understood, biology, geology, and other physical sciences also began to make sense.
- **E.** This "atomistic" idea originated with chemists but was developed further by physicists. Physicists were less interested in combining materials, however, than in adding energy, in the form of heat, to see how the materials would behave.

1. Data from these experiments fit beautifully with the idea that the material was made of atoms.
2. Scientists began to understand, for example, the ideal gas laws, a phrase that refers to the fact that if you compress a volume of gas, the pressure or temperature may increase. This phenomenon can be explained by the idea of atoms.
3. As time went by, the idea of atoms could be used to explain temperature behaviors, stresses, crystal properties, and other phenomena. The evidence for atoms was indirect, but we could see the *consequences* of their existence.

III. In the late 1800s, Ludwig Boltzmann, an Austrian physicist, developed the mathematics of thermodynamics and statistical physics.

A. Boltzmann's idea was that we should be able to make quantitative predictions about materials based on probability and statistics.

B. Boltzmann was a proponent of the idea of atoms, but in the late 1800s, the reality of atoms was still debated. Some believed that atoms were a fiction, a mathematical tool to help us explain the world, but not real.

C. Boltzmann committed suicide in 1905. His reasons were unclear, but some believe that he was frustrated by scientific antagonism toward his brilliant ideas.

D. Also in 1905, Einstein published a paper on *Brownian motion*.

1. In the early 1800s, a scientist named Brown saw that if a grain of pollen, for example, was placed in a fluid, it jiggled around. At first, Brown believed that the grain of pollen might be alive, but the same motion also occurred with other materials, such as dust.
2. In 1905, Einstein realized that Brownian motion provided direct evidence for the physical existence of atoms. He hypothesized that the movement of the tiny piece of material is caused by its being bumped by atoms surrounding it.

IV. Further evidence of the existence of atoms came from Dmitriy Mendeleev, a Russian chemistry professor.

A. Mendeleev was trying to understand all the different elements that people knew about at the time, such as hydrogen, sodium, and lithium. He recorded the name of each element, its relative weight, and certain chemical properties of each element on cards.

B. Mendeleev laid his cards out in order of increasing mass and in columns according to the chemical similarity of the elements. For example, hydrogen, the lightest element, was in the first row, and lithium was placed underneath it. Lithium weighs about seven times as much as hydrogen but is chemically similar.

C. In this way, Mendeleev formed the periodic table, which organized the atoms in a very elegant way. In some places, the table had gaps, from which Mendeleev predicted the existence of new elements, that is, fundamental materials that would be indivisible by any chemical means. Mendeleev could also predict the weights and certain chemical properties of these new materials.

D. Within a decade, gallium and germanium were discovered by scientists attempting to fill in the gaps in the periodic table. The prediction and discovery of these new elements served as profound evidence of the idea and organization of atoms.

E. In the late 1800s, people were making crude estimates about the properties of atoms. The atomic hypothesis became firm science, but it was still not deeply understood in this era.

V. Let's take a step back from this early development to look at the scientific method and the development of another model, the planetary model.

A. In the 1500s, people debated whether the earth, the sun, or something else was at the center of the universe. Some weak data had been collected, but people still did not subject the data to rigorous mathematical testing.

B. This testing began with the work of a Danish astronomer named Tycho Brahe. Brahe took excellent data on the motion of planets through the night sky.

C. Brahe had a kind of confused idea of the solar system, but he was more interested in collecting the data than in proving his ideas. This is the first step in the scientific method.

D. Brahe's assistant, Johannes Kepler, had an idea of the solar system that was similar to the ideas of Copernicus; that is, that the sun was at the center and the planets revolved around it.

  1. Copernicus believed that the planets moved around the sun in circles.
  2. Kepler carefully analyzed Brahe's data and determined that the planets do revolve around the sun, but in elliptical orbits.
  3. Kepler's achievement was in describing the data accurately; he did not attempt to explain the data.

E. If we truly want to understand something, however, we must go beyond just describing the data. The person who took this step in relation to the solar system was Isaac Newton.

  1. Born in the 1600s, Newton was perhaps the first real scientist. In the *Principia*, he laid out the scientific method.
  2. Newton applied the scientific method to the data that imply that planets move in ellipses.
  3. Newton had the idea of a universal force of gravity that kept the planets in orbit.
  4. He worked out a formula that tells quantitatively how gravity depends on the mass of objects and the distance between objects. He then applied this formula to the question of the motion of the planets.
  5. In other words, Newton started from scratch with Kepler's ideas on a deeper level; he *explained* Kepler's *description* of the data.

VI. In the late 1800s, people were satisfied with the picture of atoms as a description of nature, but they still lacked understanding of the underlying theory of atoms.

A. They were at the stage of Kepler in describing the atom, but the Newton needed to explain the atom hadn't come along yet.

B. To develop deeper understanding of the atom, we needed something beyond the physics of the 1600s–1800s.

C. What was missing was quantum physics and relativity. The transition from classical physics to modern physics had not been made, although there were some hints that this transition was soon to come.

  1. The first hint was the discovery of radioactivity, which didn't fit in with the classical scheme of atoms. Radioactivity—energy spontaneously generated and emitted from certain universal materials—was very mysterious.
  2. Another hint was the inability to calculate, using the laws of classical physics, the *glow* of heated objects. Calculations in these experiments did not agree with the observed data.
  3. In the next lecture, we will discuss these conflicts.

Essential Reading:

Weinberg, *Dreams of a Final Theory*, chapter II.

Kane, *The Particle Garden*, chapter 2.

Recommended Reading:

Lederman, *The God Particle*, chapter 3.

Calle, *Superstrings and Other Things*, chapter 7 (up to "First models of the atom").

Questions to Consider:

1. Do you believe in the objective reality of atoms? Why or why not? If so, what evidence do you consider the most compelling? If not, can you articulate why not?
2. Imagine a giant jar filled with tiny "super-duper" superballs that never lose their energy. They bounce around continuously; if you drop one on the floor it bounces back up to full height, over and over again. The jar contains many of these balls, bouncing around in every direction. Picture a piston at the top of the jar that can slide in or out without friction, but sealing the top of the jar completely. As the superballs bounce around in the jar, some will hit the piston from below, giving it a little push upward as they bounce off it. You have to push downward to prevent the piston from flying away. Now ask yourself the following:

   (a) What would happen to the force you need to apply on that piston if you suddenly doubled the number of superballs in the jar, everything else remaining the same?

(b) What precisely would happen to your force if you suddenly doubled the speed of each superball? (This is tricky! They would rebound with twice the speed, but it would also take only half as long for them to reach the piston again.)

Lecture Four

The Birth of Modern Physics

Scope: This lecture contains some stories of Planck, Einstein, Rutherford, and the early quantum physicists. What does quantum mechanics tells us about the world? How did Einstein help make the transition from nineteenth-century "classical" physics to twentieth-century "modern" physics? This lecture offers answers to those questions and a brief guide to the radical shifts in the philosophy of science around the turn of the last century, including the important role of the discovery of radioactivity, the electron, and the fact that atoms are not indivisible. This period saw the beginnings of our primitive understanding of the realistic structure of atoms.

> A philosopher once said, "It is necessary for the very existence of science that the same conditions always produce the same results." Well, they do not!...
> Do not keep saying to yourself, "But how can it be like that?" because you will get "down the drain," into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.
>
> —Richard Feynman, on quantum physics
> (*The Character of Physical Law*)

Outline

I. The ideas of classical physics developed steadily, starting with Isaac Newton in the 1600s and progressing through the 1700s, 1800s, and 1900s. This development included the concepts of e.g. forces, gravity, electricity, magnetism, energy, temperature, thermal physics, light, and sound.

II. The transition to modern physics was forced on the scientific community in about 1900 by inconsistencies between theoretical calculations and observed data. The first such inconsistency came from Max Planck's study of the *glow* of heated objects.

- **A.** This topic brings together many aspects of physics, including atoms, which move faster when heated; electricity and magnetism, which cause the glow when an object is heated; thermodynamics; and others.
- **B.** In studying this problem, classical physicists found wild discrepancies between what their calculations predicted about the color and energy emitted by heated objects and what the data actually showed.
- **C.** Planck started by playing the role of Kepler and describing, but not explaining, the data. He produced a formula that described the temperature and behavior of heated objects. The formula matched the data, but it was a description, not an explanation.
- **D.** Later, Planck himself came up with an explanation. He challenged the prevailing theory that light was a wave of electromagnetic energy, postulating that instead of electromagnetic waves, atoms emit discrete pulses of light called *quanta*.
- **E.** Planck found that his description of the data on hot objects in his formula matched his new idea, which contradicted the scientific thought of the day. He believed that he had found an interesting mathematical solution to a problem but did not really see the implications in his explanation of nature.
- **F.** In 1905, Einstein took Planck's idea to the next step in a paper on the *photoelectric effect*. This was also the year in which Einstein published papers on Brownian motion and the theory of special relativity.
  - **1.** In the late 1800s, scientists knew that if light is shone on metal, electricity is produced. At the time, the details of this photoelectric effect were a mystery, because people pictured electromagnetic radiation, or light, as a wave.
  - **2.** In this view, we would expect that intense light would produce a great deal of energy in its electrons, but this is not the case.
  - **3.** Einstein found that Planck's idea of light as quanta explained the data of what happens when intense light is shone on metal.

III. Another push toward the transition from classical to modern physics was the discovery of radiation and radioactivity.

- **A.** The idea that energy could be spontaneously generated was very exciting in the late 1800s and spurred a great deal of study and rapid development of our understanding of this phenomenon.
- **B.** One of the most important early experiments in radiation was conducted by a British physicist, J. J. Thomson, in 1897.
  - **1.** Thomson constructed a device consisting of an evacuated glass sphere connected to a high-voltage battery on either side. Using this device, he produced radiation in the sphere, called *beta radiation*, or *cathode rays*.
  - **2.** Thomson did further experiments with his device. He surrounded it with an electric field and watched the beam of radiation bend, demonstrating that the beam was electrically charged.
  - **3.** Through these experiments, Thomson deduced that the rays were negative particles and that they were very light, 2000 times lighter than the lightest element known, which was the hydrogen atom.
- **C.** Other experiments done with radiation at the time included those of Wilhelm Roentgen, a German physicist. Roentgen examined what happened when the beta rays hit the end of a device like Thomson's. He found that the beta rays stop, and another ray, a *gamma ray*, or *x-ray*, travels through the room. The x-ray is invisible but could be detected with photographic plates.
- **D.** Ernest Rutherford, a great experimentalist, did research into alpha radiation.
  - **1.** Rutherford found that alpha radiation was much heavier than beta radiation and positively charged.
  - **2.** He also found that if alpha radiation hit a target, such as nitrogen, the nitrogen could change into oxygen. The fact that one element could change into another was a radical idea at the time.
  - **3.** All these experiments combined were beginning to teach scientists that atoms were not indivisible and not immutable.
  - **4.** Rutherford had a further idea to begin to understand atoms: Cover a source of alpha radiation, such as uranium, with lead so that the lead will absorb the radiation. Next, drill a hole in one side of the lead to allow a beam of alpha particles to escape and use this beam of alpha radiation to study atoms.
  - **5.** Rutherford directed the alpha particles at a thin gold foil. According to Thomson's earlier "plum pudding model" of the atom, all the alpha particles were expected to pass through the foil and be detected on the other side. Rutherford found, however, that some of the particles bounced back, the equivalent of firing an artillery shell at a piece of tissue paper and having it bounce back.
  - **6.** To explain this occurrence, Rutherford came up with a new model of the atom: Suppose that the positive charge that we know must be contained in the atom is concentrated in the middle, and the negatively charged electrons are orbiting around it, like planets.
- **E.** This new model contradicted classical physics and introduced questions about why the orbits of the electrons didn't deteriorate and result in the disappearance of atoms.
  - **1.** A young Danish physicist, Niels Bohr, came on the scene at this time and developed the first quantum model of the atom based on the work of Planck and Einstein.
  - **2.** Bohr theorized that the orbits of the electrons in the atoms are also quantized, which would explain why the atom was stable.

IV. People began to see that nature is different on the scale of individual atoms; nature does not behave classically on this level.

- **A.** Louis de Broglie, a French prince, observed that scientists seemed to be seeing a duality—a world of both particles and waves.
- **B.** He put forth the idea of a *wave-particle duality*: At the quantum level, an object can be both a wave and a particle at the same time.
- **C.** If this is true for the quanta of light, which we now call *photons*—that is, if light is both a wave and a particle—maybe the same is true of electrons.
- **D.** de Broglie applied this theory to electrons in the atom and discovered that Bohr's model of the quantum nature of electron orbits was explained. This was the first step from a crude theory to a more rigorous mathematical framework called *quantum mechanics*.

Essential Reading:

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapters 2.2 (from p. 18 on), 2.3, and 2.4.

Schwarz, *A Tour of the Subatomic Zoo*, chapter 1, up to p. 9.

Weinberg, *Dreams of a Final Theory*, chapter IV.

Recommended Reading:

Greene, *The Elegant Universe*, pp 86–97.

Riordan, *The Hunting of the Quark*, chapter 1.

Lederman, *The God Particle*, chapter 4 and the first half of chapter 5, up to "A peek under the veil."

Calle, *Superstrings and Other Things*, chapters 21 and 23.

Questions to Consider:

1. If electromagnetic radiation (light) strikes a metal surface, electrons can be ejected. Two properties of these ejected electrons are relatively easy to measure: their energy, and their intensity (number/sec emitted). The incoming light also has two basic properties that can be easily adjusted: brightness (intensity) and color (frequency). These are completely independent properties.

   (a) Suppose light is a classical wave, like waves rolling up to a beach. (The ejected electrons are like pebbles being scattered.) How would both of the properties of the ejected electrons (listed above) depend on each of the properties of the incoming light?

   (b) Suppose light is, instead, a stream of "photon particles." How would your answers to part (a) change?

2. Suppose you were given three small radioactive samples: one is an alpha emitter, one is a beta emitter, and one is a gamma emitter. Imagine you were given the rather horrible order to eat one, put a second one in your pocket, and hold the third one in your hand. Which sample would you choose for which place and why? (Yes, I know, it's a rather disturbing choice, but there is a logical "best answer," assuming that you cannot choose "none of the above.")

Lecture Five

Quantum Mechanics Gets Serious

Scope: What were the key early developments of quantum mechanics? What did it teach us about the world and why would anyone believe such a theory? This lecture serves as a qualitative introduction to the work of Schrödinger and Heisenberg, along with the Dirac equation (which marries quantum physics with relativity) to describe electrons.

Electrons are the first fundamental particle discovered: the carrier of electricity, constituent of all atoms, and the key to understanding chemistry! In this lecture, we highlight properties of the electron: what does it mean for a "pointlike object" to have properties, and what might they be? The lecture also introduces *spin* and tries to make sense of this purely quantum mechanical concept. We look at Dirac's equation, which predicted antimatter and turned out to be smarter than he was, and discuss the birth of *quantum electrodynamics*, or *QED*. (We'll talk about the words *quantum*, *electro*, and *dynamics* and put them together to get a sense of what QED tells us about.) We conclude with the experimental discovery of antimatter and the neutron and their significance for the developing story.

> Anyone who is not shocked by quantum theory has not understood it.
> —Niels Bohr

> I repeated to myself again and again the question: "Can nature possibly be as absurd as it seemed to us in these atomic experiments?"
> —Werner Heisenberg (*Physics and Philosophy*)

Outline

I. Quantum mechanics forms the conceptual underpinnings of particle physics. For our purposes, we need a qualitative sense of quantum mechanics.

A. Quantum mechanics was born when data contradicted the predictions of classical physics, which was a well-developed field in the late 1800s.

B. In the early 1920s, a German physicist, Erwin Schrödinger, was asked to give a colloquium on the ideas of Louis de Broglie about wave-particle duality.

1. An audience member suggested that what was needed in the study of quantum waves was a wave equation, similar to what had been developed for sound waves and water waves.
2. Schrödinger began to develop an equation that could describe the wave nature of an electron.
3. The Schrödinger equation yielded quantitative results for certain questions, such as the energy of an electron, but the values were inexplicable by classical physics.

C. The remaining question, then and now, is, "What is waving?" The best interpretation that can be given came from another German physicist, Max Born.

1. Born's interpretation of the wave is that it is a *probability wave*.
2. To understand this term, think of a water wave. It is high in some places and low in others. In a probability wave, the high places represent locations where the electron is likely to be found, and the low places represent locations where it is unlikely to be found.
3. This analogy does not mean that the electron is traveling in a wave-like pattern. It travels on some path, and from the wave equation, we see certain places where it is likely to be and certain places where it is not likely to be.
4. This probabilistic interpretation of Schrödinger's equation was the key to making quantum mechanics "work" and for describing a range of other physical phenomena.
5. Some physicists and philosophers to this day still debate and discuss the structure and meaning of these "interpretations."

D. Another German physicist, Heisenberg, also played a key role in developing quantum theory.

1. Heisenberg was more interested in developing equations that described observable phenomena, such as the light that goes into, and is emitted from, radiation-testing apparatus.

2. Heisenberg's equations were *matrix equations* and were later found to be mathematically equivalent to Schrödinger's equation.
3. Heisenberg also derived the *uncertainty principle*: In certain well specified cases, if you know one quantity well, then you are obligated to lose information about another, related quantity.

E. Quantum mechanics is counterintuitive, but we should keep in mind that although it has some mysterious aspects, it is rigorous science; it does predict the outcomes of experiments.

II. Almost as soon as quantum mechanics was developed in the 1920s, it was observed that the new theory had a conceptual problem: Special relativity was not completely consistent with the early version of quantum mechanics.

A. The early version of quantum mechanics was excellent for describing small objects that moved slowly but not for objects that moved quickly, such as electrons in orbit in an atom. Special relativity was needed to describe the rapid movement of objects.

B. Paul Dirac, a British physicist, tackled the problem of marrying quantum mechanics and relativity.

C. The name for this theory is *quantum electrodynamics*, or *QED*.

1. *Quantum* applies because it's a quantum theory.
2. *Electro* applies because the description is of electrical phenomena.
3. *Dynamics* applies because the theory describes why electrons move the way they do.
4. QED looks at the question of why electrons behave the way they do in relation to quantum mechanics and relativity.

D. In 1927, Dirac published the *Dirac equation*, which was motivated purely by the beauty of the mathematics, not directly by data. Dirac believed that the formulas of quantum mechanics and relativity should match.

1. The Dirac equation is consistent with quantum mechanics and relativity, and it makes certain quantitative predictions. It is also, like Schrödinger's equation, a wave equation.
2. This theory predicts the behavior of an electron in certain situations, such as when it's running free, when it's bound to an atom, and so on.
3. This theory evokes as a hypothesis the idea that an electron is a point particle.
   - **a.** When we think of a point, we think of a dot, similar to a period. But even a period is spread out to a degree and is made up of ink.
   - **b.** An electron, in contrast, is truly a point; it is not spread out over space.
4. How do you describe a point particle? We can say that it has certain characteristics, such as mass and electric charge.
   - **a.** Another property of electrons is *spin*. Think of a spinning ball; the "amount" that the ball is spinning, or its *angular momentum*, can be measured (in certain units).
   - **b.** In the same way, electrons spin, all at the same rate. This rate, derived from Dirac's equation, is *spin 1/2*.
5. Another consequence of the Dirac equation is the following:
   - **a.** If you solve the equation for the behavior of an electron traveling in a cathode ray tube, for example, you get another solution.
   - **b.** The second solution also reveals the existence of a particle with a certain mass and a certain magnitude of charge, but the "sign" is the opposite. The particle is the opposite of the electron, with a positive electrical charge.
   - **c.** We call this particle discovered in the second solution *antimatter*. In other words, Dirac's equation in the late 1920s predicted the existence of antimatter.
   - **d.** Dirac himself did not understand or pursue this result of his equation, but in 1932, antimatter was discovered in photographic emulsions in the laboratory.

III. A final discovery in the transition from classical physics to quantum physics was the neutron, which fit in well with the then-current understanding of the atom.

A. Protons had been known since the early 1900s. A positively charged, massive object, the proton is the fundamental building block of the nucleus.

B. Chadwick discovered the neutron, which is like a partner for the proton.

1. If we think about a simple nucleus, such as one with two protons, we can imagine that the protons should repel each other because they are both positively charged.
2. Some new force of nature must exist that binds these two protons together. That force is not electricity, nor is it gravity; it is the *nuclear force*, or the *strong force*.
3. The data being collected in the 1930s on the nucleus suggested that something else must exist in the nucleus other than protons. Some electrically neutral particle is needed to help the whole system stick together. That is the role of the neutron.

C. At this point, physicists had begun to develop a coherent story of quantum physics, just as they had earlier developed a coherent story in classical physics.

1. This worldview, based on the components of the atom, was reasonably satisfactory but not complete either.
2. In the period from the 1930s to the 1950s, physicists began to see that just as the classical picture of atoms was not complete, neither was the quantum picture of the protons and neutrons.
3. The next step was to understand the nuclear picture. Although the explanation of the electrons was satisfactory, the nuclear part of the story was a bit more complicated. In the next lecture, we will travel into the nucleus.

Essential Reading:

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 2.6.

‘t Hooft, *In Search of the Ultimate Building Blocks*, chapter 3.

Recommended Reading:

Greene, *The Elegant Universe*, pp. 97–108, 112–116.

Lederman, *The God Particle*, chapter 5 (second half, starting from “The man who didn’t know batteries”).

Calle, *Superstrings and Other Things*, chapter 22.

Wilczek and Devine, *Longing for the Harmonies*, Fifth Theme.

Questions to Consider:

1. Why is quantum mechanics considered so puzzling? What single aspect of quantum theory do you find most counterintuitive or hard to believe or understand?
2. What practical uses can you think of for antimatter? (This is a “real-life” question, not a Star Trek question. You cannot assume that antimatter just appears from nowhere; it would have to be produced somehow.)

Lecture Six

New Particles and New Technologies

Scope: This lecture looks at particle physics in the first half of the twentieth century, including cosmic rays, and the discovery of the muon. We also see the dawn of nuclear physics with Yukawa's theory of nuclear force and ensuing "models" of nuclei. We discuss the discovery of the pion, along with bubble chambers and cloud chambers, the first modern tools to detect subatomic particles.

> Who ordered that?
>
> —I. I. Rabi (on the unexpected discovery of the muon)

Outline

I. Up to now, we have been talking about the transition from classical physics to modern physics. We have moved from a "mechanistic," clockwork worldview that enables quantitative predictions about all aspects of the world to a quantum worldview that still enables predictions, but not about everything, and encompasses some indeterminacy.

- **A.** Part of what drove this transition was the discovery of radioactivity and subatomic particles, including the electrons and the nucleus.
- **B.** The worldview in the 1930s used quantum mechanics as a framework and understood protons, electrons, and neutrons as building blocks.
- **C.** This worldview enabled scientists to study larger and larger subjects, such as chemistry, using these fundamental ideas.
- **D.** Of course, this view also enables us to look at deeper levels and try to find the ultimate building blocks of the world.

II. In the 1930s, the nucleus was still somewhat mysterious. It was seen as the heart of the atom, containing the bulk of matter.

- **A.** Scientists were beginning to discover how protons and neutrons in the nucleus hold together.
  1. They knew that protons tend to fly apart because they have like charges, but some strong nuclear force binds protons together, and both protons and neutrons feel this force.
  2. In the 1920s, experimentation with protons began. For example, a beam of protons could be directed at some material, then scattered to see what would happen.
  3. The development of nuclear physics, followed by particle physics, began, then, as a mix of experimental work and new theories. The interplay between experiment and theory is always significant in physics, and this was especially true in the 1930s.
- **B.** In the mid-1930s, a Japanese theorist named Yukawa hypothesized a mechanism that would mathematically describe the strong nuclear force, which was one of the central mysteries of physics at that time.
  1. To understand Yukawa's model, we must examine *forces* in general, that is, the interactions between objects.
  2. Think of a simple push-and-pull situation, such as two electrons coming near each other, feeling a repulsion because they are both negatively charged, and flying apart.
  3. Newton called this type of situation *action at a distance*. The electrons feel the force even though they don't touch. The same principle keeps the earth in orbit around the sun; earth is attracted to the sun by the force of gravity.
  4. A modern idea along similar lines is the idea of force as mediated by a particle.
  5. In the same situation of two electrons approaching each other, imagine that one electron emits a photon, the fundamental quantum of electromagnetic radiation. The act of emitting this photon forces the original electron backward; the photon's interaction with the other electron also repels it, similar to two people tossing a medicine ball back and forth. The force between the two electrons is mediated by the photon.

6. This description is not to be taken literally; it is an analog for what the mathematics describes in the theory of quantum electrodynamics.

C. Yukawa wondered if this same idea of forces could be applied to the strong nuclear force.

1. The strong nuclear force is different from electricity in a variety of ways. It is, for example, at least 100 times stronger than the electrical force.
2. The strong nuclear force is also a contact force. If the protons and neutrons are far apart, they don’t feel any force, but if they are close, they are bound together quite tightly.

D. Yukawa posited that the strong nuclear force might be mediated by a particle.

1. This particle would be similar to a photon, but unlike a photon, it would be massive. A photon, the transmitter of electricity, is itself massless.
2. Where would the energy come from to create this new particle? Classical physics would not allow energy to be created from nothing, but quantum mechanics, using Heisenberg’s uncertainty principle, allows a loophole in the laws of classical physics.
   - **a.** According to the uncertainty principle, energy can be created out of nothing, but only for a very short time.
   - **b.** The *virtual particle* of the strong force, then, is created for a very short time, travels from one proton to the next, then disappears.
   - **c.** The uncertainty principle is quantitative; it states that if a certain amount of energy is “borrowed” from nature, only a certain amount of time for the existence of the particle is allowed.
   - **d.** The particles can travel no faster than the speed of light and only for a certain maximum distance, which explains why protons and neutrons must be close to each other to feel this force.
3. Yukawa also deduced what the mass of his new particle would be. His conclusion was that the particle must be less massive than a proton but more massive than an electron. Because the mass of this particle is in the middle, Yukawa called it a *meson*.

E. For the first time, a theorist, Yukawa, had predicted the existence of a radical new particle of nature. Later, many other mesons were discovered, and Yukawa’s particle became known as the *pi meson*, or *pion*.

F. With this idea of mesons, a new era was introduced. Scientists could begin doing calculations in the realm of nuclear physics.

III. Experimentation continued, especially in Europe, up until the hiatus of World War II.

A. Experimentalists were eager to create a pion and document its existence with real, direct evidence.

B. To achieve this goal, a source of energy was needed, and scientists looked to *cosmic radiation*, which is natural radiation from the stars, the sun, and other sources.

C. Alpha and beta rays are, in effect, electrically charged particles. When such a particle passes through matter, its electric charge attracts and repels all the electric charges in the atoms and tears the atoms apart. When a particle passes through matter in this way, it leaves an *ion trail*, a trail of atoms that have been temporarily torn apart.

D. Particle detectors were developed to provide evidence of the passage of these submicroscopic particles. For example, a charged particle could be sent through a photographic plate. The film could then be developed to reveal an ion trail.

E. Another form of particle detector was the cloud chamber.

1. Imagine a container filled with gas. If you were to pull a piston on the chamber very rapidly, the gas would cool and would tend to condense.
2. The gas can condense along the walls of the chamber or along an ion trail.
3. In other words, an electrically charged particle is sent through the chamber, the piston is pulled, and a chain of droplets forms along the ion trail, verifying the existence of the particle.

F. The bubble chamber is similar to the cloud chamber, but it uses a superheated liquid that is on the verge of boiling. Again, bubbles from boiling liquid can form along the edges of a container or along an ion trail.

G. The next step is to analyze the somewhat puzzling picture provided by the particle detectors to identify the details of the particles that passed through.

IV. Recall that all these experiments were aimed at finding evidence for Yukawa's pion.

- **A.** Scientists were looking for a trail with certain well-defined characteristics, including a certain mass, electric charge, and so on.
- **B.** In 1937, such a trail was seen, but it was not clear whether the observed particle was Yukawa's predicted pion or not.
- **C.** Pions were "invented" to explain the strong nuclear force; therefore, they should be strongly absorbed by nuclei. Yet, the results from various particle detectors revealed that the particles travel from one end of the detector to the other, hardly interacting at all.
- **D.** These mysterious new particles, which were not behaving as pions should, were called *muons*.
  - **1.** The muon was similar to a heavy electron.
  - **2.** Muons with both positive and negative charges existed.
  - **3.** The mass of the muons was in between the mass of protons and that of electrons.
  - **4.** Finally, muons were radioactive. Every now and then, a muon would be seen decaying into an electron at the end of its track. It was radioactively unstable; it could transform itself into an electron.
  - **5.** Even today, the muon remains something of a mystery; its purpose is unclear.
- **E.** It was another ten years before Yukawa's pion was discovered, but the discovery of the muon was, in a sense, the birth of particle physics.

Essential Reading:

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapters 2.5 and 3.1 (to p. 47).

Schwarz, *A Tour of the Subatomic Zoo*, chapter 3 (up to pp. 30) and chapter 8.

Recommended Reading:

Riordan, *The Hunting of the Quark*, chapter 2.

Calle, *Superstrings and Other Things*, chapter 8 and the first half of chapter 24 (up through "Pions").

Questions to Consider:

1. If the pion were suddenly significantly more massive than it currently is, what would happen to the range of the strong nuclear force (that is, would protons "feel" each other's presence when they are farther apart—at long ranges—or would they need to be even closer together still—at short ranges)?
2. What happens to muons as they travel downward through the atmosphere? (What happens to their overall number and their average energy?) What happens to an individual muon when it decays? Where does all the energy from cosmic rays ultimately go?
3. How much, and what types of, background radiation are you exposed to daily? Where does it come from? To what extent do you think it is a significant health hazard?
4. Colorado has a much higher flux of cosmic radiation than sea-level states (because it has much less atmosphere for protection), but overall cancer rates are not noticeably higher in Colorado than in sea-level states. What conclusions might you draw?

Lecture Seven

Weak Interactions and the Neutrino

Scope: What is an *interaction*, and how does that differ from the concept of a force? What is a weak interaction, and how is it connected to radioactivity? How weak is weak? In this lecture, we address these questions and look at the importance of weak interactions in the sun. We also examine the carriers of weak forces, W and Z particles, and the modern idea of transmutation. We close with the birth and early story of the neutrino. What are these ghostlike particles, and how can we speak of a particle with no mass?

> I have done a terrible thing. I have postulated a particle that cannot be detected.
> —Wolfgang Pauli

Outline

I. One of the most interesting developments in the history of particle physics was the discovery of a new force of nature, the weak force, and a particle that is associated with that force, the neutrino.

- **A.** In the 1930s, scientists were concerned with fundamental forces of nature, such as electrical and magnetic forces, gravity, and the strong nuclear force.
- **B.** Today, instead of *force*, physicists usually use the term *interaction*. The act of two electrons repelling each other can be thought of as an electrical interaction.
  - **1.** As we said in the last lecture, on a microscopic level, we might think of one electron generating a photon and transmitting it to another electron. This photon causes the recoil between the two electrons.
  - **2.** Instead of an electric force between the two electrons, what happens is more of an interaction between an electron and the photon it creates. On the transmitting end, one electron transforms itself into an electron and a photon, and on the receiving end, an electron and a photon transform into an electron.
- **C.** In the 1930s, scientists were studying various types of radiation, particularly beta radiation because it is unusual.
  - **1.** In beta radiation, an electron flies out, and when we look at what's left behind, we see that a transformation has occurred.
  - **2.** The simplest beta decay we can think of is as follows: After a period of time, a neutron in the lab radioactively decays, spontaneously transforming into an electron and a proton.
  - **3.** What causes this transformation? We now explain it with the term the *weak force*, a weak interaction of nature. This is not an electromagnetic interaction, not the strong nuclear force, but a transformative force.
  - **4.** This way of thinking about a force was new in the 1930s because the weak force was not a push or a pull, but a force of nature that causes radioactive decays. We now know that the weak force does exert more traditional pushes and pulls, but at the time, it was thought of only as transformative.

II. Remember that when we think about forces of nature now, we visualize the involvement of a force carrier.

- **A.** Electromagnetism, for example, involves the photon. The Japanese physicist Yukawa proposed that the strong nuclear force involves the pion as a force carrier.
- **B.** What kind of force carrier is involved with the weak force? We now call this force carrier the *W particle* (or *W boson*) for "weak particle." Because the W particle can have either positive or negative charge or zero charge, we speak in terms of *W plus*, *W minus*, and *Z* (for "zero charge"). These are three possible force carriers for the weak force.
- **C.** Why is this interaction termed "weak"? If a neutron decays and a proton and an electron are generated, that interaction does not seem weak.
  - **1.** The reason the interaction is called weak is that it is improbable.
  - **2.** The interaction seems improbable because the W particle is extremely massive. As we learned in discussing the pion, if a particle is created from nothing—essentially "borrowed" from nature—then the more massive it is, the shorter the amount of time is allowed for it to exist.
  - **3.** The W particle is so massive that the amount of time it can be borrowed from nature is extraordinarily short. That is the origin of the improbability of the weak force.

D. Why are we concerned with the weak force?

   1. The weak force plays some role in nature. For example, a number of radioactive materials decay in this way, and weak decays usually mean long lifetimes.

   2. In medical technology, the long lifetime of certain materials is important to allow doctors to see the images.

   3. A more important role of the weak interaction takes place inside the sun. The main power generation in the sun is the strong force, but the sun would not work with only the strong force.

      a. Protons interact with other protons in the sun, but the strong force alone will not bind them into a stable nucleus.

      b. The weak force is needed to transform one of those protons into a neutron to form a stable nucleus.

      c. We need the strong force as the source of the sun's energy, but we also need the weak transformation to stabilize the final product.

   4. The weak force also plays a role in building larger and larger nuclei, as in carbon, nitrogen, oxygen, and so on.

E. How do we see the weak force? Beta decays are one of the ways that we have observed this force in nature. In studying the weak interaction, physicists have also come to see the significant role of the *neutrino*.

   1. A neutrino is a particle of nature, similar to an electron or a proton, but it feels only the weak force. Because it has no electric charge, it doesn't feel electricity; it has no mass; and it has no strong interaction with protons and neutrons.

   2. For this reason, the neutrino can emit and absorb only W bosons or Z bosons, which is a highly improbable event.

III. The "inventor" of the neutrino was Wolfgang Pauli, a member of the generation that was developing quantum mechanics.

A. Pauli formulated the *Pauli exclusion principle*, which states that two identical electrons cannot be in the same place at the same time. This idea is at the heart of chemistry.

B. Pauli also formulated tentative ideas in studying beta decays.

   1. If we again think of a simple beta decay, we can measure both the original energy of the system and the final energy of the system. The result is that the system has more energy to start with than it has in the end.

   2. This disappearance violates the principle of conservation of energy and was, to Pauli, an unacceptable possibility.

   3. Momentum is also not conserved in beta decay. The electron and proton created in beta decay often travel off in a similar direction, rather than traveling in opposite directions, as we would expect.

   4. Pauli imagined that a third particle must be involved in this interaction to explain the contradictions in conservation of energy and conservation of momentum. Later, this third particle was named the *neutrino*.

   5. Pauli shied away from his own proposition of a particle that could not be detected, saying, "I have done a terrible thing."

C. Another physicist, Enrico Fermi, developed the idea of the neutrino into a mathematical framework. Fermi's mathematics, which assumed the existence of the neutrino, enabled correct calculations of many other beta decays.

D. In 1956, Cowan and Reines set up a giant detector outside a nuclear reactor to increase the chances of occurrence of this low-probability event, and they found direct evidence of neutrinos.

IV. How do we make sense of a particle with no mass and no charge?

A. The answer lies in the fact that the prediction of the neutrino consolidates a great deal of physical data in a simple way.

B. This particle belongs to the class of particle called *leptons*, the same class as the electron and the muon.

C. Like the electron, the neutrino has spin 1/2. As we will see, all neutrinos spin in the same way, and anti-neutrinos spin in the opposite way.

D. When a neutrino is created as a result of a beta decay, it shares some properties of the electron that was also created. Thus, it is an *electron-flavored neutrino*. *Muon-flavored neutrinos* can also be created.

E. In technology, neutrinos are just beginning to become a wonderful astronomic tool to give us a picture of the inside of the sun, which would otherwise be impossible to see.

Essential Reading:

Schwarz, *A Tour of the Subatomic Zoo*, chapter 1 (pp. 10–11), chapter 2.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 2.10 and pp. 48–55.

Recommended Reading:

Lederman, *The God Particle*, chapter 7 ("The Weak Force").

Wilczek and Devine, *Longing for the Harmonies*, Third Theme.

Questions to Consider:

1. Why *specifically* did Wolfgang Pauli feel compelled to postulate the existence of a nearly invisible particle?
2. In your entire lifetime, probably only one solar neutrino will interact with an atom somewhere in your body. Using this fact, roughly how big a tank of water would you need if you wanted to observe a neutrino interaction ten times a day? (After you "guesstimate" your answer, you might go on the Web to look up the size of the neutrino detector at SuperKamiokande in Japan.)

Lecture Eight

Accelerators and the Particle Explosion

Scope: World War II spawned a fresh burst of scientific energy and achievements that lasted for decades. Particle accelerators were born. What were these machines? How did they work and what did they do? In some respects, this era saw the origin of "big science" in the United States. With the birth of accelerators came a steady stream of new discoveries. Fundamental particles began to appear by the handful. What were they like, and how could they be organized to allow physicists to make sense of what they were detecting? We include a quantitative discussion of energy, setting numerical scales to make sense of the particle discoveries.

> As experimental techniques have grown from the top of a laboratory bench to the large accelerators of today, the basic components have changed vastly in scale but only little in basic function. More important, the motivation of those engaged in this type of experimentation has hardly changed at all.
>
> —Wolfgang Panofsky (*Contemporary Physics*)

Outline

I. Research in nuclear and particle physics slowed considerably during World War II, but the war had a significant influence on some aspects of science.

- **A.** In the United States, a number of bright physicists were brought together in the Manhattan Project to develop the atomic bomb. This project was more about technology and engineering than physics, but the exchange of ideas among physicists on the project brought about an explosion of ideas in theoretical and experimental physics.
- **B.** Politically, physicists were seen as valuable to the U.S. government for national security purposes. A certain amount of prestige became attached to the science of physics, which led to funding and public support for projects.

II. Throughout the 1910s–1930s, physicists were using natural sources of radioactivity, such as uranium or cosmic radiation, in their experiments in nuclear physics, but natural radiation does not offer very high energy.

- **A.** One reason that physicists were looking for higher energy sources stems from quantum mechanics.
  - **1.** The uncertainty principle states that if we want to examine very small objects, we need higher levels of energy.
  - **2.** To understand this idea, think of water waves and their wavelengths, which are defined as the distance from one peak of a wave to the next. As water waves propagate, the wavelength can be changed. Thus, if you create a wave in a pond by moving your hand in the water and you increase the rapidity of the movement of your hand, the waves tend to get closer together.
  - **3.** In general, then, if you want to look at a small object, you need a small wavelength of light, which is created with more energy.
- **B.** Einstein's $E = mc^2$ also led physicists to seek higher energy events in order to observe new phenomena.
  - **1.** Energy is required to produce a particle that has a mass; the amount of energy required is the mass × the speed of light^2.
  - **2.** The speed of light^2 is a large number; in other words, we need a good deal of energy to produce a new particle.
  - **3.** Further, if we're looking for more exotic particles of higher and higher mass, we must have more energy to produce them.
- **C.** Energy can be measured in various unit systems. Particle physics uses a unit called the *electron volt*, or *eV*, which for our purposes, is just a scale for measuring energies.
  - **1.** The measure 1 eV is a rather small energy, which might be the typical kinetic energy of an electron in an ordinary atom.
  - **2.** The typical energy of a proton inside a nucleus is 1 million eV, or an *MeV*.
- **D.** In the 1920s and 1930s, scientists were trying to build particle accelerators. These are mechanical devices used to create small particles, such as an electron or a proton, using a lot of energy. The accelerator then

smashes the particle into a target to enable scientists to learn about other interactions and to see what other particles are generated.

1. One such device was the Van de Graaff accelerator, which could generate up to a million volts and allowed the study of protons and neutrons. To look at the constituents of protons and neutrons, however, requires much more than a million volts.
2. Ernest Lawrence, a Midwestern physicist, made a breakthrough in the development of a particle accelerator with his *cyclotron*.
3. The idea of the cyclotron is as follows: If you want to speed up an electron or a proton, you need some voltage, such as from a battery. If you set up a high-voltage battery and produce sparking from one terminal to the other, that voltage difference accelerates the charged particles.
4. Lawrence's idea was to direct the sparks from the high-voltage battery into a region with a large magnet. The charged particle in the magnetized region will travel in a curved path. When the particle reaches a certain point in the curve, the poles on the battery are reversed, and the particle is sent back through the device. Each time the particle is pushed back through the battery, it gains energy.
5. The resulting beam of protons can be used in various ways, for example, aimed at a target, much as Rutherford had been doing.

E. With this innovation, funding for physics increased, and the United States began building centralized national labs with particle accelerators. The energies produced increased steadily; right after the war, the energy reached 200 million eV.

1. Recalling Yukawa's work with the pion, physicists knew that about 100–150 million eV was required to produce one pion. Ultimately, these particles were created in the cyclotron.
2. By the 1950s, the energies of the accelerators reached 1 billion or more eV, which is termed *GeV* for giga-electron volt.

III. At the same time that the particle accelerators were developing, the particle detectors were improving.

A. In the early 1900s, Rutherford had used students to count particles by eye as they hit a phosphorescent screen. Later, the cloud chamber and bubble chamber were used to detect and identify particles.

B. The invention of the bubble chamber in 1952 improved the ability to observe high-energy particles because of the high density of the liquid inside it. The higher the density, the greater the likelihood of observing interactions.

IV. At this time, the need for automating the detection process grew, although computers were not yet in common use.

A. As the devices for acceleration and detection improved, hundreds of new particles were discovered. Physics experienced an explosion of information but lacked an organizing principle to characterize these discoveries.

B. Physicists wanted to learn the properties of these new particles, including their mass, electric charges, lifetimes, and spin. Physicists also discovered that almost all these new particles interact strongly, or have a high probability of interaction, and have very short lifetimes.

C. A classification system began to emerge for these particles, based on their interactions. The terminology is as follows:

1. *Hadrons*—From the Greek for "thick," strongly interacting particles, such as the proton, neutron, or pion.
2. *Leptons*—From the Greek for "light," not strongly interacting, such as the electron, muon, or neutrino.

D. Hadrons were subcategorized as follows:

1. *Baryon*—From the Greek for "heavy"; what one might think of as truly a particle, such as a proton or neutron.
2. *Meson*—The intermediary particles, such as the pion.

V. In the 1950s, a great deal of overwhelming information was being collected. The situation in the physics community was similar to what it had been in the field of chemistry in the 1800s.

A. The physicists in the 1950s needed some kind of organizing principle, similar to the periodic table for the chemists, to begin to classify their data.

B. In the next lecture, we discuss the first attempts by theorists to organize these data. Ultimately, we will discover that this seemingly complex story is really quite simple.

Essential Reading:

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 3.2.

Recommended Reading:

Riordan, *The Hunting of the Quark*, chapter 3.

Lederman, *The God Particle*, chapter 6.

Questions to Consider:

1. In a cyclotron, the amount of time it takes a non-relativistic particle to swing around a circle in the magnetic field is *independent* of the energy of the particle. (In other words, all particles go around at the same frequency, no matter what their energy.) Why would Einstein's theory of relativity contradict this principle at super-high energies?

2. Under what circumstances do you suppose a cloud chamber would be more suitable as a particle detector, and when might one rather have a bubble chamber? Can you think of advantages and disadvantages for each? (You might want to go web-hunting at some of the major particle physics sites to see what kind of detectors are being used today. Detector technology is a field that continues to make great strides all the time!)

3. Energy can be measured in many units (just as length can be measured in feet, or miles, or meters). Particle physicists often use "eV" but a more common measure of energy is the "Joule" (J). You can figure out one from the other (just as you can figure your height in cm—if you know it in inches—as long as you know how many cm there are in one inch!) The conversion you need is $1 \text{ eV} = 1.6 \times 10^{-19}$ J. Now, Einstein's $E = mc^2$ (mass × speed of light^2) tells you what a particle's "rest energy" is. If you plug in the mass in kg (kilograms), and use $c = 3 \times 10^8$ m/s (meters/sec), the energy automatically comes out in Joules, not eV! Given that the proton mass is 1.7×10^{-27} kg, see if you can find out the "rest energy" of a proton, in eVs. (To check yourself, notice that I said that by the 1950s, energies had reached 1 billion eV, and that was, not coincidentally, the era that the anti-proton was finally observed.)

Lecture Nine

The Particle "Zoo"

Scope: As the accelerators churned out new particles, many were easy to understand and categorize, but some appeared especially strange, with a curious mix of strong and weak properties that seemed, at first, to be mutually contradictory. The proper description of these *strange particles* was a turning point in our developing understanding of the zoo of particles. How many particles exist? How can we keep track of, and make sense of, this zoo of particles? New words were coined for new particles and concepts, including *mesons* and *baryons*, *hadrons* and *leptons*, *bosons* and *fermions*, *flavor* and *families*. The words are alien and unfamiliar, but they help organize our thinking about the world. We'll talk about these words and try to connect them with the stories and particles we've already learned about to give them form and context. What happened to our theme of "simplicity"? What is the meaning of "fundamental" if there are hundreds of fundamental particles? We will also see how the idea of a *conservation law* helped to organize these particles, along with the various properties, often referred to as *quantum numbers*, of the individual new particles.

> Physics is simple, but subtle.
>
> —Attributed to P. Ehrenfest

Outline

I. In the 1950s–1960s, particle physics was experimentally driven.

- **A.** The advent of particle accelerators enabled physicists to produce whole families of new particles and observe their tracks in bubble chambers and more sophisticated detectors.
- **B.** This lecture addresses these families of particles and the first steps toward organizing the wide range of data that were being collected at the time.

II. In the 1950s, some unusual tracks began to appear in bubble chamber images. The particles that left these tracks were called *strange particles*, because scientists could make no sense of some aspects of the tracks.

- **A.** First, some V-shaped tracks appeared in the images, caused by what was then termed a *V particle*.
  - **1.** The V particle seemed to appear out of nowhere, but it could have been generated by the decay of an electrically neutral particle that left no track in the bubble chamber.
  - **2.** More puzzling was the question of why these tracks took so long to appear. Producing particles in a bubble chamber usually results in a strong interaction; producing a neutral particle should result in a rapid decay. Why, then, is the V particle so widely separated from anything else?
  - **3.** Another strange aspect of these V tracks was that they almost always appeared in pairs. This phenomenon is called *associated production*.
- **B.** The first part of the explanation for these strange particles came from a young theorist named Murray Gell-Mann.
  - **1.** Gell-Mann proposed that fundamental particles might have another property besides the ones that had already been considered, which were mass, charge, and spin. Note that the measures for all these properties are called *quantum numbers*.
  - **2.** Gell-Mann proposed that there was one more quantum number associated with these particles, which he called *strangeness*.
  - **3.** For example, strangeness 0 meant that the particle was "normal," such as a proton, neutron, or pion. The V particle, an exotic new particle produced with higher energies, has strangeness 1.
- **C.** How did Gell-Mann's proposition explain the associated pairs of the V tracks?
  - **1.** When a strong interaction takes place, such as a pion hitting a proton, and an event occurs, such as a transformation or the creation of a new particle, the strong force preserves total strangeness. In other words, if an interaction begins with strangeness 0, it must end with strangeness 0.
  - **2.** This conservation of strangeness is an idea that is easy to accept because it follows similar ideas of conservation. We know, for example, that energy is conserved in an interaction, as is momentum and electric charge.

3. This concept explains the associated pairs of the V particle. One particle will have a strangeness number of +1, and one will have strangeness –1.

D. How did Gell-Mann's idea explain why these particles have such long lifetimes?
   1. The strong interaction of nature conserves strangeness, but the weak force does not. The weak force transforms a neutron into a proton; it can also transform a strange particle into a non-strange particle.
   2. This explains why the particles last so long. Once a strange particle has been produced, it cannot decay strongly if it doesn't have enough energy to produce other, lighter particles with nonzero strangeness. (The strong force must conserve strangeness.) The particle must "wait," then, for the improbable weak decay to occur, which takes a longer time.

E. Throughout the 1950s, Gell-Mann's theory was tested and shown to fit with a wealth of data. As a conservation theory, it was useful in trying to understand complex phenomena.
   1. Under the principle of conservation of electric charge, if a neutron strikes a proton, the resulting charge is 0 + 1 = 1. That event may also produce some new particles, but the production is limited by conservation of charge; the *total* charge produced must equal 1, which it started with.
   2. In the same way, the conservation of strangeness limited the possible outcomes of these accelerator experiments.

III. Let's briefly review the naming conventions for these particles.

A. Strongly interacting particles are called *hadrons*, including protons, neutrons, pions, and strange particles.

B. Weakly interacting particles are called *leptons*, including electrons, muons, and neutrinos.

C. Hadrons are further subdivided into *baryons* or *mesons*.
   1. Baryons are particle-like. For example, the proton and neutron, which are baryons, serve as building blocks of nuclei. They also have half-integer spin.
   2. Mesons were proposed by Yukawa as force carriers. After the pion came heavier versions of pions, such as kaons and rho particles. All mesons have integer amounts of spin.

D. Each of these particles can still have various other quantum numbers. For example, some mesons may have strangeness 0, some may have strangeness +1, and so on.

E. Another way to categorize these particles is based solely on spin. Although this concept is very complex, for our purposes, we only need to realize that every particle of nature has either half-integer or integer spin. This fact is significant.
   1. Particles with half-integer spin are called *fermions*. Again, fermions are what we tend to think of as particles, such as electrons and muons.
   2. Particles with integer spin are called *bosons*, named after an Indian physicist of the early twentieth century, Satyendranath Bose.
      a. This physicist argued that any particles that have integer spin, even two identical particles, can exist right on top of each other.
      b. The most famous example of a boson is the photon, the "particle" of light. We can easily visualize light sitting on top of other light; the result is just brighter light.
      c. Fermions are the opposite; they cannot be made to exist in the same place at the same time.

IV. The goal in the 1950s was to make some sense of the data from all these different particles. In fact, scientists were beginning to observe deeper patterns, which served as hints that some part of the story of physics was still missing.

A. For example, consider the proton and neutron, which are electrically different but, in every other respect, almost identical. We call such particle "partners" *doublets*.

B. Later, we learned that there are many particles with similar partnerships. For example, the three kinds of pions, pi+, pi–, and pi 0, form a triplet.

C. When we look at particles with strangeness, we discover a strange meson, called the *kaon*.
   1. The kaon can have various strangeness numbers. In fact, there are four different kaons, a positive one, a negative one, and two neutral ones.
   2. What's the different between the two neutral kaons? One of them has positive strangeness and one has negative strangeness. The two neutral kaons are a kaon and an anti-kaon.

D. How can we explain these doublets, triplets, quadruplets, and so on? Gell-Mann created an organizational scheme to assign numbers and categorize these particles. He called his scheme the *eight-fold way*, a tongue-in-cheek reference to Eastern philosophical writings, but it was still a description of the data rather than an explanation.

E. Later, Gell-Mann came up with an idea to explain what seemed like the overwhelming complexity of these particles. He suggested that all these strongly interacting particles, such as the kaons, pions, and protons, are constructed of three simple building blocks, which he called *quarks* after a phrase in James Joyce's *Finnegan's Wake*.

F. As we get further into this course, we will discuss the theory and phenomenology of quarks, which are the ultimate building blocks.

G. Before we begin our discussion of quarks, however, we must leave the world of particles briefly for a look at forces. In the next lecture, we will further develop the idea of force as mediated by a particle.

Essential Reading:

Schwarz, *A Tour of the Subatomic Zoo*, chapter 4.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 4.2.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 5.

Recommended Reading:

Riordan, *The Hunting of the Quark*, chapter 4.

Lederman, *The God Particle*, chapter 7 ("The Strong Force").

Calle, *Superstrings and Other Things*, chapter 24, sections on "Particle Classifications," "Conservation Laws," and "Strange Particles,"

Questions to Consider:

1. The following nuclear reaction is observed to occur frequently (it is a *strong* interaction):

   pi– + p => K+ + Sigma–.

   What this means in words is that an incoming pion with charge –1 (that's the pi–) can strike a proton (charge +1), and the result is a positively charged kaon (the K+) and a negatively charged Sigma particle.

   (a) Verify explicitly that this reaction is not forbidden by charge conservation.

   (b) The K+ meson has strangeness number +1. What can you conclude about the strangeness number of a Sigma– particle?

   (c) Later, the K+ meson is seen to decay into a pi+ and a pi0 (one positively charged pion and one neutral pion). Could this reaction be a "strong" decay, which happens quickly (meaning that the K+ will have a very short track; the decay will happen immediately), or is it a "weak" decay, which means that it takes a long time (and, thus, the K+ meson should leave a long track)? Why and how do you know?

2. Consider the following four particles: a neutrino, a positive pion, a proton, and a positive kaon, or K+ (see question 1 for more information about the K+). Which one(s) is (are) a hadron? a lepton? a meson? a baryon? a fermion? a boson?

3. Consider the following nuclear reactions. Based only on the principle of charge conservation, which one(s) are allowed and which are forbidden to occur? Are any that are allowed by conservation forbidden based on the principle of baryon number conservation*?*

   Note: *n* means neutron, *p* means proton, *e* means electron, *pi* means pion. Protons have charge +1, electrons have charge –1, neutrinos are neutral. For all other particles, the electric charge is written as part of the name. For example, *pi*+ means a pion with charge +1, *pi*– means a pion with charge –1, and *pi0* means a neutral pion, that is, with charge 0.

   (a) e + p => neutrino + n
   (b) e + n => neutrino + n + pi–
   (c) e + n => anti-proton + n
   (d) e + p => anti-proton + proton
   (e) e + p => pi+ + pi0

Lecture Ten
Fields and Forces

Scope: This lecture examines the concept of a field, leading to the story of modern QED, the fully quantum theory of light and particles. We look at the early trials and tribulations, the idea of a "field of particles," the 1947 Shelter Island Conference, and the concept of *renormalization*. We will also examine Feynman diagrams, the most widely used conceptual tool of particle physics. QED is perhaps the greatest theory mankind has ever produced, vindicated by quantitative tests and stunning accuracy.

In 1968, one of the participants of the Shelter Island Conference, theoretician Abraham Pais, described the state of particle physics as:

> A state not unlike the one in a symphony hall a while before the start of the concert. On the podium one will see some but not all of the musicians. They are tuning up. Short brilliant passages are heard on some instruments; improvisations elsewhere; some wrong notes too. There is a sense of anticipation for the moment when the symphony starts.

> What I am going to tell you about is what we teach our physics students in the third or fourth year of graduate school… It is my task to convince you not to turn away because you don't understand it. You see my physics students don't understand it… That is because I don't understand it. Nobody does.
> —Richard Feynman (*QED*, p. 9)

Outline

I. In this lecture, we focus on the *theory* of particle physics, how we understand interactions between objects in the world. In particular, we will examine a way of thinking about forces that is between Isaac Newton's somewhat naïve idea of action at a distance and the idea that force is an exchange of virtual particles.

- **A.** The intermediate step between these two ideas was very important and, in fact, has been integrated into our quantum picture today. This idea is called the concept of a *field*, also known as *field theory*.
- **B.** In the 1800s, electricity was explained as being similar to gravity: Two objects are far apart and, somehow, they feel an electrical force, action at a distance.
  - **1.** In trying to visualize the phenomena of electricity and magnetism, Michael Faraday, a British physicist of the mid-1800s, drew pictures—field lines—of the way he imagined the forces would manifest themselves.
  - **2.** You may have seen similar pictures or performed similar experiments in elementary school science. For example, you place a piece of paper on top of a bar magnet, then sprinkle some iron filings on top of the paper. The iron filings spread out and form curved lines that go from the south pole to the north pole of the magnet. This experiment helps you visualize lines of magnetic force, spreading out through space.
  - **3.** If you were to go off to the side of your work space with a sensitive compass needle, you could detect the compass needle deflecting because of the existence of this magnetic force field.
  - **4.** Faraday thought about field lines as being real. He imagined that if he held up a magnet, magnetic fields created by the magnet truly exist in the world, everywhere in space.
  - **5.** This idea of a force field explains how a charge that is far away can feel the force. The first charge makes the field, which exists in empty space, whether or not a second charge is present. If a second charge is added, it will react to the field, either attracting or repelling.
- **C.** Later theorists wondered whether this idea was generalizable: Could it be incorporated into the theory of quantum mechanics?
  - **1.** Dirac's equation, which married relativity and quantum mechanics, was the description of electrons in the presence of electric fields. It was the first primitive attempt at quantum electrodynamics, or a quantum theory of electricity and why things move under the influence of electromagnetic forces.
  - **2.** Yet Dirac's equation didn't incorporate the field theory. Dirac was thinking more about the electron as a particle experiencing some electrical forces. Even so, Dirac's theory worked well without incorporating the concept of a field.

D. What happens if we take into account field theory?
   1. Using Dirac's theory alone, we can calculate the energy of light, or the *spectrum*, of radiation that is emitted by a hydrogen atom.
   2. If we include the idea of the field in these calculations, we must imagine that the space between the proton and the electron in the hydrogen atom is no longer empty. It's filled with an electric field.
   3. Now that we're thinking quantum mechanically, we realize that electric fields carry an energy density and, thus, we can borrow a bit of that energy to create, for example, a virtual electron and an anti-electron. Heisenberg's uncertainty principle says that we can pull a particle/anti-particle pair out of the vacuum (if only briefly).
   4. The problem that we originally thought was pretty simple, involving one electron and one proton, becomes more complicated because we've added an electron and an anti-electron.
   5. Further, if we can produce one particle/anti-particle pair in the problem, how about two or ten or a billion? All of a sudden, the vacuum inside and around a hydrogen atom is a very complicated place. We call these virtual particles *vacuum fluctuations*.
   6. What are the consequences of the presence of an electron-positron pair? Imagine a positive charge in the middle and a negative charge that's attracted to it on the outside. In the middle, we have a (virtual) + and a (virtual) – charge. The plus will tend to shift toward the electron, and the minus will tend to shift toward the proton in the middle. The force the electron feels will change, because the electron is reacting to a different configuration of charges nearby.
   7. To determine the energy of that electron, we have to make this correction to our earlier estimate. The correction is numerically small, but we must account for an infinite number of small corrections.

E. That infinite number of corrections was a disaster for physicists in the late 1920s–1930s. When physicists tried to calculate the net total effect of all those vacuum fluctuations of the quantum fields, they discovered that the total effect on the electron, this infinite sum of progressively smaller and smaller effects, grew to be infinitely large. There was a sense that quantum field theory might not be the answer for describing nature.

II. After World War II, at the Shelter Island Conference of 1947, a group of physicists got together to share the problems they were working on and decide what they should look at in the future.

A. An experimentalist at the conference named Willis Lamb presented an experiment he had done using radar technology from the war to measure the light emitted by hydrogen. Lamb made an unexpected discovery: One of the colored lines that comes out of hydrogen is, in fact, two colors that are very closely spaced, two frequencies that are very nearly the same. This phenomenon is called *Lamb splitting*.

B. Another physicist at the conference, Hans Bethe, had heard in advance of Lamb's experimental work and began thinking of it in conjunction with vacuum fluctuations. Bethe acknowledged that he couldn't deal with an infinite number of vacuum fluctuations, but he could deal with just a few. What if he had an e+/e– pair that was produced in the vacuum? What would that do to modify the answer from the calculations about the light emitted from hydrogen? As you might guess, it splits the line.

C. The outcome of the conference was Lamb's radical result, which was in contradiction with quantum mechanics, and Bethe's hint that a quantum field theory was needed to explain the data. Many scientists started thinking about this problem of how to make quantum electrodynamics a full-fledged quantum field theory.

D. Among the other participants at the conference were Richard Feynman and Julian Schwinger. Together with Tomonaga, a Japanese physicist, they were awarded the Nobel Prize in 1965 for their work on the development of a successful quantum field theory.

III. We will try to understand the breakthrough that these scientists made—if not the details, then at least the basic premise.

A. Here's the original problem: We start with a proton in the middle. It creates a field, and that field is modified by the presence of virtual fluctuations, e+/e– pairs popping up and disappearing again. We must add up all possible contributions for one pair, two pairs, ten pairs, and so on, but when we add them up, we get infinity.

B. The inventors of QED thought that the problem was being approached from the wrong angle. If we start from a proton with an electric charge, we can measure that charge, but we don't know the bare charge of a

proton, because we can't observe a bare proton. What we observe is the proton plus all the surrounding vacuum fluctuations.

C. Instead, we should start with some unknown original charge, then add the infinite number of corrections. The final answer should be the observed experimental charge of the proton. The term for this approach is *renormalization*. The idea is to fix up the starting point of the theory so that in the end, the calculation makes some sense.

D. Renormalization seems almost like cheating. We start off with something that we don't know and we fix it up. In fact, in our problem, renormalization is worse than cheating. In order to make the calculations work, the original charge of the proton must be akin to negative infinity, because we're adding an infinite number of corrections to it, and we end up with the right answer, which we measured in the first place.

E. Why do physicists accept this approach? The reason stems from the fact that we can calculate an infinite number of things about electrons and protons, such as energies, magnetic field strength, their reactions in an electric field, and so on. We have an infinite number of observables. But we have to cheat about only two things.

1. First, we must know what the charge is going to work out to be; we can't predict that.
2. Second, we have to know what the mass is going to be. Einstein's work tells us that if we borrow energy from a vacuum, we're shifting the energy or mass of the system.
3. These are the only two quantities we have to measure. Every other physical quantity can now be calculated in this theory.

F. When scientists began doing the calculation for the Lamb shift, they found that it worked exactly. To the best ability of the experimentalist who measured the splitting, quantum electrodynamics, QED, gave the correct number.

G. The same thing occurred for every other observable that we measured, such as the magnetic strength of the electron and the energies of other orbits in the hydrogen atom. The theory was successful. In fact, for estimating the magnetic strength of an electron, QED was successful to twelve digits of accuracy.

IV. Let's examine Feynman's contribution to QED in a bit more detail.

A. Part of Feynman's genius was his ability to examine complicated problems from a different viewpoint to make them seem simple.

B. Feynman summarized his mathematical calculations in little pictures called *Feynman diagrams*. Each Feynman diagram is a symbolic representation of a mathematical equation.

C. To draw a Feynman diagram, we must use certain symbols. For particles, we draw straight lines. For example, imagine an electron moving along; if we draw a graph of its position on the vertical axis versus time on the horizontal axis, we have a straight line. The graph shows the electron moving forward in time and forward in position.

D. Now suppose that this electron has an electromagnetic interaction. The quantum view of electromagnetic forces is that a photon is spontaneously produced. Feynman's diagram for a photon is a wiggly line that leaves the electron and goes off on its own. The spot where the electron and the photon were touching for one brief instant is the interaction spot. It's the vertex where they interact.

1. What explains this occurrence? The interaction spot occurs if the photon is capable of being reabsorbed very quickly. When energy is borrowed from the vacuum to create the photon, it must be returned.
2. Perhaps there's a proton nearby, and it, too, interacts with the photon, then it recoils because it absorbs something. Both particles recoil. That's the force that the electron and the proton feel because of each other.
3. Each line, each vertex, each wiggle in a Feynman diagram represents some mathematical operation. The beauty of this approach is that you don't have to be a brilliant physicist to understand the representation.
4. This graph represents a number, and if we do the calculations to find that number, it is always between 0 and 1. The Feynman diagram rules are constructed so that this number is the probability that this process occurred.

5. Quantum mechanics tells us about probabilities of the occurrence of events. The Feynman diagram predicts the likelihood that an electron and a proton with certain given initial properties will result in certain measured final properties.

E. How does this apply to quantum field theory?

1. We might naively think of the photon traveling between the electron and proton as the electric field. That electric field could split and create an electron and a positron pair briefly, and a Feynman diagram could be drawn to represent that occurrence.
2. At a certain place in the middle of the drawing, the photon turns into a positron that runs backward and an electron that runs forward. They re-annihilate—create a photon again—because they can fluctuate for only a brief moment in time, then the photon continues on its way. This is the quantum fluctuation that we mentioned earlier.
3. This diagram could be calculated just as the first one could be. The numerical value for this diagram is much smaller than for the previous one, because there are more vertices and each vertex introduces a numerical factor that decreases the result. In other words, this is a low-probability event.
4. The game with Feynman diagrams is to start adding diagrams. We can imagine drawing more and more complicated versions of our first diagram, but those diagrams always come out smaller. The more complicated the diagram gets, the smaller its value.

F. This diagram is universal. Using this kind of diagram, we can calculate any kind of observable. We add all possible intermediate diagrams to our initial scenario, and the answer we get is the numerical estimate that we're interested in.

V. This incredibly powerful theory of QED was developed in the 1950s and truly ties everything together. We now have a theory that accounts for electricity, magnetism, light, electrons, quantum mechanics, relativity, and fields—a truly unified theory of electricity and magnetism.

A. Next, physicists started to wonder if this idea could be used to understand all the forces of nature. What about the strong nuclear force? Could we understand the interactions among protons and neutrons and pions using an idea like this?

B. When scientists had first tried to understand Yukawa's ideas about pions with a theory similar to QED, they failed. They could not make the theory work.

C. It was impossible for us to create a relativistic quantum field theory with the ingredients that we had in the 1930s–1950s, but we now have the ingredients, which we will examine in the next few lectures.

Essential Reading:

Weinberg, *Dreams of a Final Theory*, chapter 5, pp. 107–116 only.

Kane, *The Particle Garden*, chapter 4, pp. 69–70, and Appendix A.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 4.1.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 9.

Recommended Reading:

Wilczek and Devine, *Longing for the Harmonies*, Sixth Theme.

Lederman, *The God Particle*, chapter 7 (first half, up to "The Weak Force").

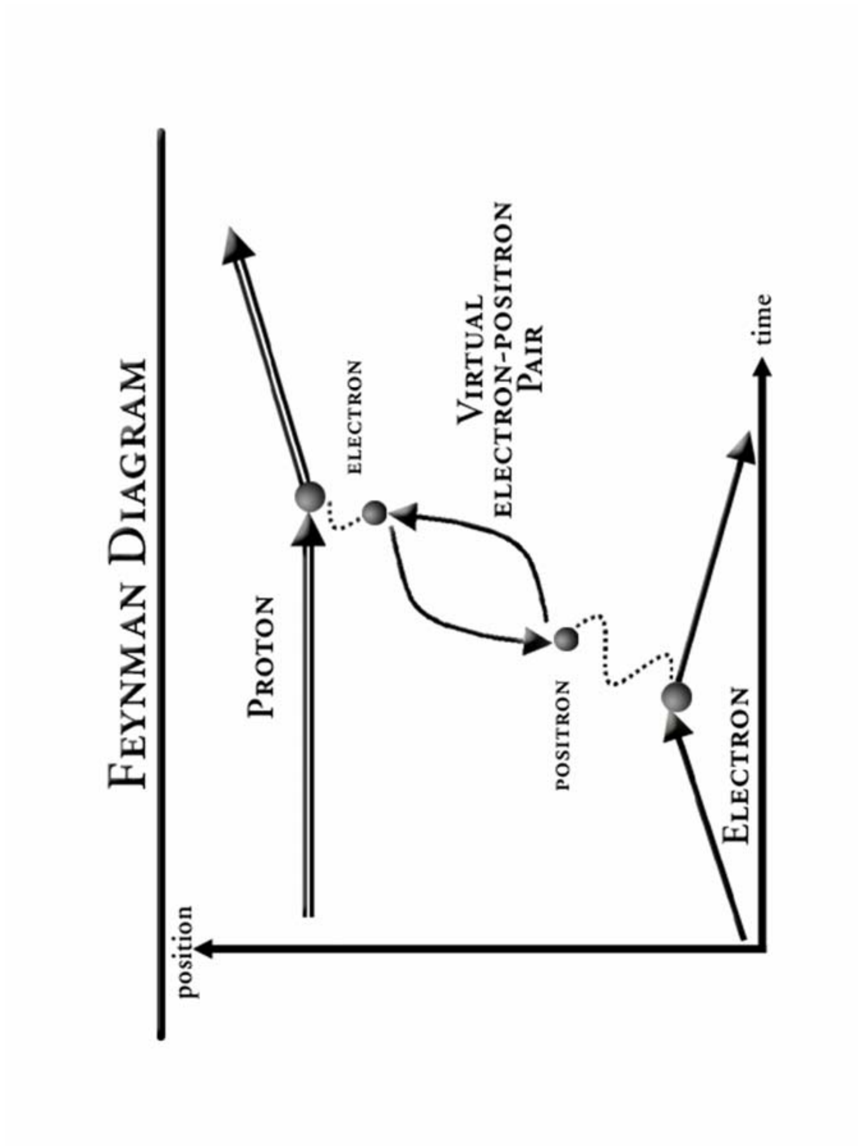
Feynman, *QED*. (You may want to take your time reading the whole book. It's a great attempt to explain the theory of QED, in surprising detail but without any math, to the general public. Worth a look if you want to dive deeper.)

Questions to Consider:

1. Try to draw a simple Feynman diagram schematically showing Rutherford's experiment (where a positively charged alpha particle scatters, or bounces electrically, off a positively charged nucleus). Note that the symbol for any charged particle is generally the same—a straight line with an arrow showing the direction of travel.
2. Classically, there is energy in the fields that surround a charged particle. Also, the strength of the electric field near a charge is proportional to 1 divided by the square of the distance from the charge. Qualitatively, why might postulating a point-like particle, such as an electron, lead to infinite energy in a classical calculation? (This is the technical issue underlying the need for renormalization.)

3. Richard Feynman once said he believed that renormalization was like sweeping dirt under the rug. What do you suppose he meant?

Feynman Diagram



Lecture Eleven

"Three Quarks for Muster Mark"

Scope: In this lecture, we attempt to crack the hidden code of the particle zoo and discover that the hadrons (strongly interacting particles) are fundamental but not elementary. What evidence is there to guide us to a deeper understanding? Could these particles be made of something else—mini-atoms themselves? The breakthrough idea of quarks provided the answer, along with a return to simplicity. This lecture offers a guide to the early "quark picture," the names of these new particles, their properties, and their roles in making up the world. We also look at the importance of successfully predicting the existence and properties of new fundamental particles of nature with a new type of periodic table of particles.

> Three quarks for Muster Mark!
> Sure he hasn't got much bark
> And sure any he has it's all beside the mark.
> —James Joyce, *Finnegan's Wake*

Outline

I. We return now to the situation in experimental particle physics in the 1950s–1960s. As you recall, hundreds of particles were being discovered, and scientists were trying to pinpoint their commonalities to come up with an organizational scheme.

A. Despite the complexity of the particle zoo, physicists had an inkling that some underlying simplicity might exist. Their clue to this simplicity stemmed from the fact that protons and neutrons didn't seem to be point-like.

1. Let's distinguish between a fundamental particle, which we've been talking about all along, and an elementary particle. An elementary particle would be a true building block of nature—a dot, a point with properties.
2. Electrons seemed to be elementary particles of nature, but the protons and neutrons did not. Even in the 1950s and 1960s, scientists saw clues that the proton might actually be spread out in space, that it might be made of something.
3. The atom was known to be spread out in space even when the periodic table was generated. An atom has a size of about 10^{-10} meters, which is tiny, but it's not 0. The atom is spread out over some distance scale.

B. In the late 1950s, Robert Hofstadter made a similar discovery for the proton itself and received the Nobel Prize in 1961.

1. Hofstadter used a beam of electrons, which are truly point-like particles, as a kind of magnifying glass to examine the proton. Ordinary light cannot be used to look at a proton, because the wavelength of visible light is huge compared to the tiny size of a proton. By focusing a beam of electrons on the proton, Hofstadter went back to an analogy to Rutherford's experiment to examine the atom.
2. Rutherford directed alpha particles at an atom and deduced that the atom has a nucleus inside and electrons on the outside. If the energy of the incoming beam is increased, smaller and smaller distance scales can be seen.
3. At Stanford University, Hofstadter produced a beam of electrons that was high enough in energy to probe to the size of the nucleus.
4. Remember that Rutherford observed that every now and then, a particle would bounce backward, indicating that there was something hard, like a little nugget, in the middle of an atom. Hofstadter saw the exact opposite occurrence. The electrons would go into a proton and, perhaps, bend at a small angle, but in general, they went straight through.
5. This observation is an indicator that the proton is, itself, like the plum pudding. It's just a smear of electric charge. By looking at the details of how the electrons bounced, Hofstadter was able to deduce the size and distribution of the electric charge.
6. He found that the proton was a spread-out, positive charge over a size scale of about 10^{-15} meters (a *femtometer*). That measure is 100,000 times smaller than an atom, but it's not 0.

C. Hofstadter demonstrated that the proton is not a point, but if that is true, then it is not an elementary particle. Physicists started to wonder if some other particle was inside the proton, spreading out positive electric charge.

D. Another piece of evidence, even more abstract, pointed to the fact that the proton is not an elementary particle.

1. Recalling Dirac's equation and the development of QED, physicists wondered if the same theory that had been used to estimate the strength of magnetism of an electron could be applied to a similar calculation for the proton.
2. But that calculation failed miserably, implying that the starting assumption, namely, that the proton is a point, is incorrect.
3. Murray Gell-Mann and George Zweig, working independently, came up with the breakthrough idea that the proton is built up of three smaller objects. Gell-Mann called them *quarks*, because they were quirky particles that were not directly observable.
4. Quarks are tiny objects that are bound together very tightly. According to the Heisenberg uncertainty principle, they are spread out, presumably over a distance scale of about a femtometer, and they form a cloud. That's what a proton is: nothing more than three quarks held together by some strong force of nature.
5. There are three different types of quarks, whimsically named by Gell-Mann, *up*, *down*, and *strange*.

II. Gell-Mann wondered if all of the particles that were being discovered in bubble chambers could be explained with this idea. He proposed that every baryon, every one of the strongly interacting particles that acts like a particle, such as the proton and the neutron and all its heavy partners, are all made of just three quarks.

A. Different combinations of these quarks are possible, such as three up quarks, two up quarks and a down quark, and so on. The zoo of particles can be understood as combinations of three building blocks.

B. Now the question is: Will this model work? Will we be able to describe in detail all the particles we see?

1. Let's go back to the strongly interacting particles that are the subject of experiments at the particle accelerators, the hadrons.
2. Remember that hadrons can be either baryons or mesons. Baryons are particle-like, such as protons and neutrons. Mesons were, at least originally, thought of as force carriers.
3. Mesons and baryons are different. Mesons, for example, can be produced easily, but the total number of baryons is always conserved.
4. What is a meson, then? According to Gell-Mann's quark model, a meson should be a quark and an anti-quark tightly bound together, a binary system spinning together.
5. Given Gell-Mann's rules, any combination of quarks can be formed, and these must match up with one of the known particles.

C. Physicists first wanted to see if this model could be made quantitative; to do that, they had to come up with a list of properties of quarks.

1. For example, what is the mass of a quark? What is its charge? What is its spin? Those three properties are almost all we have to describe about quarks, because they are postulated to be point-like particles, just like electrons.
2. What is the spin of a quark? Gell-Mann proposed that all quarks have spin 1/2, just like electrons and protons.
3. How does that spin affect the particles that quarks make up, such as a meson? A meson consists of a quark of spin 1/2 and an anti-quark of spin 1/2. How can they combine? Depending on the direction of the spin, they combine to form mesons with spin 0 or spin 1 (just as $1/2 - 1/2 = 0$, and $1/2 + 1/2 = 1$).
4. What about protons? In this model, Gell-Mann proposed that a proton is two up quarks and one down quark. They can't all spin in a clockwise direction because if they did, the result would be three halves, which doesn't work. Instead, two of them are spinning clockwise and one is spinning counterclockwise. The equation $1/2 + 1/2 - 1/2$ yields the correct answer for the spin of the proton.

D. Using this model, we can look at a particle from the data and try to determine its quark makeup or do the reverse; that is, start tabulating all the logical possibilities from the model and see if every logical possibility matches with some particle that has been found. In this way, we discover that there really is a one-to-one correspondence. Every particle has a description, and every description can be found in the laboratory.

III. Even though this seems to be a good model, it does have some problems.

A. For example, we have never seen one quark by itself in a bubble chamber or a pair of quarks. We only see them bound together in sets of three or as a quark and an anti-quark.

B. That fact was puzzling in this early era, and in fact, for many years, the quark model was dismissed by most physicists as no more than a mathematical construct to help organize the zoo of particles.

C. Later, we saw growing evidence for the reality of quarks, including tracks in bubble chambers (jets) that come indirectly from quarks.

IV. Let's return to our discussion about adding up the properties of quarks to get the properties of the objects themselves.

A. Consider the property of mass. If a proton is three quarks—two ups and a down—we might ask: What is the mass of each of those three quarks?

1. Gell-Mann suggested that perhaps the up and the down quark were very similar to each other, each of them carrying about one-third of the mass of a proton. If we put three of them together, we get a proton mass.

2. If the up and the down quarks are similar in mass, then what would happen if we put an up and two down quarks together? The result would be a neutron. According to the quark model, given that up and down weigh about the same, the neutron and the proton should weigh about the same, and they do. This model explains, then, why certain particles come in pairs or partners.

3. Similarly, the three pi mesons can be understood as just different combinations of up and anti-down or down and anti-up quarks, but they all should weigh about the same, and indeed, the three pions form a triplet that weighs about the same.

B. The quark theory is really only crude with respect to masses. It does a better job with other properties, e.g. consider how well the model holds up to the data when we look at electric charge.

1. Gell-Mann proposed that the up quark has charge 2/3 and the down quark has –1/3. Keep in mind that the proton has charge 1, and the electron has –1. The charges for the quarks seemed bizarre.

2. No one had ever seen an object in the laboratory that had electric charge of 1/3 or 2/3, which should leave a distinctive pattern in a bubble chamber. The more electric charge a particle carries, the greater the density of the bubbles it produces. The charges that Gell-Mann was proposing should leave a clear signature.

3. Gell-Mann accounted for this discrepancy by noting that quarks always come in either pairs or triplets. Remember that a proton has two up quarks and a down quark. The equation for its charge, then, is 2/3 + 2/3 – 1/3, resulting in 1. A neutron, which has one up quark and two down quarks, would be 2/3 – 1/3 – 1/3 = 0, which is the electric charge of the neutron.

4. As we look at other particles, we see that the charges are predicted in the same way. All the quantum numbers add up and make sense to form a coherent picture.

C. We can perform similar calculations for strangeness.

1. Remember that some strange tracks had been found in bubble chambers in the 1950s, and Gell-Mann had proposed that they were the result of a new property of matter, a quantum number, similar to electric charge. He called this property *strangeness*, and the strangeness number was always 1, or –1 (or 2, or –2).

2. The quark model now explains the strangeness number. We just count up how many strange quarks are present. If we have a baryon that consists of one up, one down, and one strange quark, that particle should have strangeness 1. If we have a particle that has one up quark and two strange quarks, that would be a particle with strangeness 2.

3. Again, the calculations matched the data beautifully. The strange quark would have to be a little bit heavier than the up and down quarks because the strange particles were a little bit heavier, but this knowledge allowed physicists to make predictions of other particle masses.

4. By looking at an up-down-strange combination, we can estimate the mass of the strange quark. If we then make a prediction about the mass of an up-strange-strange combination, that's roughly what its mass turns out to be.

5. What if we had a particle that consisted of three strange quarks? That would be a triply strange baryon, and nobody had ever seen such a thing. Just as Mendeleev had found holes in his periodic table a

hundred years earlier, this lack of a triply strange baryon constituted a hole in the organization of quarks. Later, this object was found; it's called an *omega particle*.

V. The strange quark doesn't occur very frequently in nature. It is heavier than the other two quarks but has an electric charge that is the same as the down quark. It seems almost like a heavy partner of the down quark, much as a muon is a heavy partner of an electron.

A. Why do we have strange quarks in nature? Our bodies and almost everything around us are mostly made of up and down quarks, but we still have these heavier, somewhat mysterious particles that do, occasionally, occur in nature.

B. Physicists, myself included, are still investigating the details of this story, but the fundamental idea was proposed in 1964 and it's still part of our standard model of particle physics today.

C. As we will discover, there are more particles and forces, and we have to try to fit all these ideas together. At this point in the course, we have a descriptive model, but we still need the underlying theory to explain it.

Essential Reading:

Schwarz, *A Tour of the Subatomic Zoo*, chapter 4.

Kane, *The Particle Garden*, chapter 4, pp. 53–60.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapters 2.7–2.8.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 8.

Recommended Reading:

Lederman, *The God Particle*, chapter 7, section on "The scream of the quark."

Calle, *Superstrings and Other Things*, chapter 24, section on quarks.

Questions to Consider:

1. Given that the K+ particle is a meson with strangeness +1, which one of the following choices gives the "quark makeup" of a K+? (Hint: the u quark has charge +2/3; the d and s quarks each have charge –1/3. The strangeness of an s-quark is [somewhat perversely] called –1, not +1.)

(a) u and anti-s (b) u and s (c) d and anti-s (d) d and s (e) u and anti-d

2. The delta++ is a baryon with charge 2. It is not strange. Which one of the following choices could be the quark makeup of a delta++?

(a) u u u (b) d d d (c) uud (d) udd (e) anti-u anti-u anti-u

3. A pi+ is a u anti-d meson. A pi– is the anti-particle of a pi+. What is its quark makeup?

Lecture Twelve
From Quarks to QCD

Scope: Fully understanding the world requires describing not just the *players* but the *forces* they feel. If quarks are the particles, how do they interact with one another? The answer to that puzzle has a curious (and, at first, misleading) name: They carry a new kind of charge, a *strong charge*, described by *color*. A fledgling theory arose in the 1970s, called *QCD*. We'll unpack the etymology of that acronym to make sense of it, just as we did for QED. QCD is a formidable mathematical theory, but the results are elegant and comprehensible. Quarks are *confined* together, they stick together fiercely, and if we try to pull them apart, we inevitably make more (ordinary) particles. On the other hand, when they get very close to each other, the strong force fades away to nothing, and we can make quantitative predictions with relative ease. We will look at further experimental evidence for the existence of quarks and discuss why we might believe in these particles that can never be seen, even in principle.

> Our job in physics is to see things simply, to understand a great many complicated phenomena, in terms of a few simple principles.
>
> —Steven Weinberg, Nobel Prize Lecture, 1979

Outline

I. Gell-Mann and Zweig introduced the idea of quarks into the physics literature in 1964. This idea helps to describe and explain a good deal of data, but it was quite controversial for many years.

- **A.** Already by the 1960s, there was a sense in the physics community that a crude model was not good enough. Physicists wanted to be able to make concrete and rigorous statements about how the world works. This goal went hand-in-hand with the belief that the world really is simple, and that simplicity can be described and explained.
- **B.** The goal of particle physics, starting from the introduction of quarks, was to come up with a theory, a mathematical framework, in which one could calculate and predict any observable involving subatomic particles.
- **C.** Physics already had a framework that was successful for describing electrical forces, quantum electrodynamics. Physicists looked to QED as a kind of template, wondering if a quantum field theory could be developed for the strong force.
  1. The particle of interest in quantum field theory is the quark, because the theory is put forth to examine strong forces; it focuses on the hadrons and their constituents.
  2. In QED, every particle possesses electric charge. Charge is essential in QED because it tells us the strength of the interaction.
  3. Unfortunately, we didn't know the analog of charge for the strong nuclear force. We knew that quarks carry something, but what? They have electric charge, which means that they have electrical interactions, but electrical interactions don't explain why the quarks bind together.
  4. In fact, electricity would make quarks tend to fly apart. Two up quarks, for example, have the same charge. Electricity makes them want to fly apart, but they can be bound together in a proton with a down quark. We need to identify some much stronger force to overwhelm the electricity and bind quarks together.
- **D.** Some evidence and theoretical arguments in the 1960s pointed to a new quality of nature that would play the role of electrical charge for quarks. Scientists eventually pulled this evidence together into a formal theory, which was even more complicated than QED.

II. What is this extra quality that scientists were looking for?

- **A.** Think about the delta particle, a kind of heavy version of a proton. It decays strongly and rapidly and turns into a proton. In the quark model, the delta is three up quarks.
- **B.** The delta particle has spin 3/2. It is a combination of three up quarks, all spinning clockwise. A quantum physicist would object to this statement because an up quark has spin 1/2, and we can't put two up quarks (or three) into the same quantum state.

C. The only way out of this dilemma is found in quantum mechanics, which allows particles to be put together if they are distinguishable, that is, if there's something different about them.

D. We know that we can put an up and a down and a strange quark together. We also know that we can put two ups and a down together as long as some of them spin clockwise and some, counterclockwise. But how can we put three up quarks together? The answer is that there must be some other property of quarks, a new quantum number.

E. Apparently, this new number must have three possible values. The new variable was called *color*, even though it is not related to visible color. (It's *just* a name.) Physicists now spoke of blue, green, and red quarks.

F. If we start from the idea that quarks possess color, then we can explain how three seemingly identical quarks can be put together to form a delta particle. Various other pieces of evidence also validated the idea that color was, in fact, a new degree of freedom.

G. Some scientists thought that this new property might also be the charge that is responsible for binding quarks together. This charge is called *color charge*, and the force that arises when color charges are near each other is *color force*.

H. Another puzzle was why quarks combine in threes to make baryons.

   1. If we think of a color wheel, the metaphor is a good one. A color wheel has three primary colors, and if the three primary colors are added together, the result is white, which is a sort of neutral color.

   2. If we combine three quarks and they form white, then we have no net color left. Thus, a white object and another white object, such as two protons, do not attract each other particularly strongly. A red quark and a blue quark, on the other hand, feel an enormously strong force, a hundred times stronger than the electrical force, which is what binds them.

   3. We must note that protons do have a little distribution of color charge inside them that makes them begin to attract as they get closer. They feel no force until they are about a femtometer apart, then they stick very strongly.

I. How does this theory work for mesons? These particles are built not of three quarks but of a quark and an anti-quark.

   1. This metaphor works for that situation, too. A color and its anti-color are straight across from each other on the color wheel, and they also add to white.

   2. A meson, which is a quark and an anti-quark, would be red and anti-red, for example. If these are combined, they will attract very strongly because they're different colors, but they also form white. As with a baryon (such as a proton), a meson will feel nothing most of the time until it gets close, then it feels the strong force of nature.

J. At this point, the idea of color was still not a theory. It lacked a mathematical framework that would be similar to the one for QED. In this framework, however, instead of having two electrical charges, we would have three color charges. The name for this quantum field theory of color forces is *quantum chromodynamics*, or *QCD*.

III. QCD took a long time to develop, in part because the mathematics of three is more complicated than the mathematics of two.

A. In QED, when we have a charged particle, it has an electric field around it. That's a classical way of thinking about the force created by electricity.

   1. How do you visualize photons in this classical picture? If you jiggle the charge, you're jiggling the electric field, which propagates like moving water on a pond and makes the wave that travels out. When you jiggle an electric charge, classically, you get an electromagnetic wave. In the quantum mechanical view, the "jiggle" is the photon.

   2. In the same way, if we have a colored object and there's a color field around it, if we were to jiggle it, that would be the classical way to propagate the strong force.

   3. What is the particle of the strong force? If we have to give a name to the "jiggle" in the color field, we call it a *gluon*.

B. The gluon is essentially the force carrier of this strong color force, and it really is like glue. It makes things stick together incredibly strongly. We might picture a proton with three colored quarks surrounded by this color field.

C. One of the complexities of this color theory is the following:
    1. If we have an electric charge and it emits a photon, that particle, the jiggle of the field, is itself electrically neutral. An electron has charge, but the photon does not.
    2. When we work out the math with the color forces, however, we discover that the jiggles in the color fields are themselves colored; a gluon has color charge. This means that as a gluon is traveling along, it can interact with another gluon. Gluons can make gluons, can make gluons!
    3. This is part of the reason that the strong force is so strong, so much stronger than the electric force. We start with two color charges, and they produce a color field between them, which enhances itself spontaneously.
    4. If we think in terms of Feynman diagrams, we might draw one diagram with some gluons on it, then we would have to draw another diagram with more gluons and gluons meeting gluons and gluons forming all sorts of complicated structures. Further, because the force is so strong, the diagrams don't get smaller as we add more complexity. The numerical calculations in QCD are extremely difficult.

D. We can calculate some of the consequences of QCD. For example, imagine an experiment in which you are trying to pull two quarks apart.
    1. As you pull, the gluonic field is stretched. Gluons are bosons. They are attracted to other gluons. You will start to get more and more gluons, stretching in a line between those two quarks.
    2. The more you stretch the field of gluons, the more glue you have and the tighter the quarks will pull. As you pull these quarks apart, a force of nature similar to a rubber band is pulling them back together.
    3. If you do the calculations for this experiment using QCD, you discover that it is impossible to get the quarks out of a proton. The more you try to pull them apart, the stronger the strong force becomes. It actually grows with distance, unlike all the other forces we know about, such as gravity or electricity, which become weaker as objects get farther apart.
    4. What had seemed like a dilemma for Gell-Mann's quark model, namely, "Why haven't we ever seen a quark if they are real?" is now shown to be a mathematical consequence of the theory.

IV. Let's turn to another question about QCD: Why should we believe in a theory that's so hard to calculate with?

A. Let's approach this question from another direction: What if we try to squeeze two quarks together?
    1. We can do this if we work with a proton that is struck with very high-energy particles. High energy means that the distance scales are very short.
    2. If we're looking at two quarks close together, the situation is again much like a rubber band. When we stretch the rubber band, it tends to snap back, because the system has a lot of energy and the forces are strong. If we try to squeeze a rubber band, however, there's no resistance at all.
    3. The same thing happens in QCD. When the quarks are at distances much smaller than about a femtometer (10^{-15} meters), the forces become very weak.
    4. Inside of a proton, the three quarks are almost free particles. If they get a little bit too far away, they are snapped back, but while they're in the proton, they're sort of loosely bound.

B. From the early 1970s, when this theory was proposed, until today, physicists built higher energy machines and finer microscopes and discovered that the quarks are less and less strongly bound. When the bonds are looser, the calculations are easier to perform.

C. This is a wonderful twist. Usually, as we build more sensitive machines, we get more complicated results. In this theory, however, the opposite is true. If we think in the language of Feynman diagrams, the coupling gets weaker; therefore, those complicated diagrams become numerically less important and the calculations become easier and more reliable.

D. Again, this is not proof that QCD is correct, but it is certainly a compelling reason to take it seriously. The more high energy the experiment is, the more accurately we're able to test and verify it.

V. There are other reasons that scientists give credence to quarks and QCD, relating to the concept of confinement.

A. What would we see in the laboratory if we hit a quark very hard?
    1. If we hit one quark with an electron beam and it goes flying off, the other two sit behind for a moment because of their inertia, but one of them is running away, stretching that rubber band. A stretched rubber band, or in this case, a stretching gluonic field, has a great deal of energy in it. All the energy that the experiment gave to the particle is now going into the gluonic field.

2. What happens in quantum mechanics if a lot of energy is in a small space? A quark/anti-quark pair can be produced. Matter and antimatter can be produced spontaneously out of that energy.
3. As the rubber band stretches, it might snap back, which would leave behind a rattling proton, but it might also essentially break. The rubber band breaks and, at the point of breaking, a particle/anti-particle pair is produced.
4. Remember, we have one quark running away and two quarks left behind. We produce a quark/anti-quark pair. How will they line up? The quark that is produced will stay behind and the anti-quark will go along with the quark that is running away. We're left, then, with a baryon. We started with a baryon of three quarks, and we end with a baryon of three quarks.
5. However, we've also produced a quark/anti-quark pair, a pion or a meson, a heavier version of a pion. If we have enough energy, the rubber band might snap a number of times while the quark is running away, resulting in a stream of pions running away from a baryon.
6. Again, that's exactly what we see in laboratories. These are called *quark jets*. When an electron or a particle is smashed into a baryon, we can actually see a straight line of particles flying off, constituting almost direct evidence of the existence of quarks.

B. We identify other fairly direct arguments for the existence of quarks.

1. Think about Rutherford's experiment in the 1900s, the prototype particle physics experiment: striking a target with a beam of particles to see how they scatter. The idea is to determine what's inside the target by looking at how particles bounce off it.
2. This experiment has been repeated countless times in different guises. Hofstadter, for example, did a similar experiment with electrons hitting protons and determined that the proton was like a smear of electric charge. The energies he was using, however, weren't high enough to see down to the level of a quark.
3. What if we use higher energy still? Remember, the higher the energy, we use, the smaller the particles we can see. We would think that at a high enough energy, we would begin to notice that there really are nuggets, little hard objects, inside the proton.
4. In the 1960s, a fabulous physics facility was built, called the Stanford Linear Accelerator Center (SLAC). SLAC is essentially a series of straight-line accelerators, resulting in an enormously high-energy beam of electrons.
5. In the early 1970s, this beam was aimed at protons, similar to the Hofstadter experiment but at higher energies and with greater magnification. As in Rutherford's experiment, every now and then, an electron would bounce backward. This offers direct physical evidence that the electron was hitting something solid instead of running into a smear.
6. At first, scientists were skeptical that this phenomenon was the result of quarks; instead, the particles that were being hit were called *partons*, for "parts of protons."
7. As time went by, however, and the experiment was refined, physicists began to make quantitative conclusions about, for example, the charge of this object. In fact, the charges turned out to be 2/3 and –1/3, which is just what the quark model said they should be. The spin also turned out to be 1/2, just as the quark model predicted.

C. Over a period of five to ten years, more data were collected from this experimental procedure, which is called *deep inelastic scattering*. The result of these experiments was that we could see the consequences of quarks on the whole system, even though we couldn't see the quarks themselves.

Essential Reading:

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapters 3.3 and 4.1.2

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 13.

Recommended Reading:

Riordan, *The Hunting of the Quark*, chapters 5–7 and 10.

Lederman, *The God Particle*, chapter 7, the section on "Rutherford returns" and from "The strong force revisited" to the end.

Wilczek and Devine, *Longing for the Harmonies*, Seventh Theme.

Questions to Consider:

1. Considering the history of growing evidence for quarks, at what point (if ever) do you think you would have joined the “bandwagon” of physicists who believed in the existence of quarks?
2. Do you think any physicist will ever detect a “free quark” in the lab? Why or why not? What consequences would such a discovery have on the theory of QCD?

Timeline

Useful online source of original papers: http://dbserv.ihep.su/hist/owa/hw.part1

Prehistory: 400 B.C. .... Democritus proposes *atomos*, the indivisible fundamental building blocks of matter.

1861–1868 .... James Clerk Maxwell unifies electricity and magnetism in a series of papers and proposes the electromagnetic nature of light.

1869 .... Mendeleev designs the periodic table of the elements.

1895 .... Discovery of x-rays (Wilhelm Rontgen, Nobel Prize, 1901).

1897 .... Discovery of the electron (J. J. Thomson, Nobel Prize, 1906).

1896–1900 .... Discovery of alpha, beta, and gamma rays (Pierre and Marie Curie, Nobel Prize, 1903; Henri Becquerel, Nobel Prize, 1903; Ernest Rutherford, Nobel Prize, 1908).

1900 .... The concept of quanta, E = h nu (Max Planck, Nobel Prize, 1918). J. J. Thomson proposes a "plum pudding" model of the atom.

1905 .... Albert Einstein's "miracle year": special relativity, the photon concept with application to the photoelectric effect, and Brownian motion (Nobel Prize, 1921).

1909 .... Charge of the electron measured (Robert Millikan, Nobel Prize, 1923).

1911 .... Discovery of the atomic nucleus (Ernest Rutherford, with Hans Geiger and Ernest Marsden).

1912 .... Cosmic rays first observed (V. F. Hess, Nobel Prize, 1936, with Anderson). Cloud chamber invented (Charles Wilson, Nobel Prize, 1927, with Compton).

1913 .... Bohr model of the atom (Niels Bohr, Nobel Prize, 1922).

1915 .... General relativity (Albert Einstein).

1918 .... Emmy Noether's theorem relating symmetry to conservation laws.

1919 .... Rutherford observed first nuclear transmutation (alpha on nitrogen gives oxygen + proton). Proton as a fundamental particle is named.

1923 .... Louis de Broglie argues for wave-particle duality (Nobel Prize, 1929). Arthur Compton shows the particle-like nature of x-rays (Nobel Prize, 1927).

1925 .... Pauli formulates the exclusion principle and postulates new quantum property of the electron (Nobel Prize, 1945). This property, the spin, was introduced and quantified by Goudsmit and Uhlenbeck. Quantum mechanics developed in matrix form by Werner Heisenberg (Nobel Prize, 1932), followed by Erwin Schrödinger's wave mechanics (Nobel Prize, 1933).

1926 .... Born introduces the "probability interpretation" (Nobel Prize, 1954). The term *photon* is coined (Gilbert Lewis).

1927 .... Heisenberg's uncertainty principle. Wigner introduces *parity*.

1928 .... Dirac's relativistic wave equation (Nobel Prize, 1933).

1930 .... The neutrino is postulated (Pauli, named by Fermi). Cyclotron invented (Ernest Lawrence, Nobel Prize, 1939, and M. Stanley Livingston). Max Born says, "Physics as we know it will be over in six months."

1931 .... The Van de Graaff accelerator is invented. Dirac predicts antimatter.

1932 .... Positron discovered (Carl Anderson, Nobel Prize, 1936). Neutron discovered (James Chadwick, Nobel Prize, 1935).

1934 .... Beta decay theory written down (Fermi). Yukawa's theory of nuclear force (Nobel Prize, 1949).

1937 .... Experimental evidence for mesotron (now called muon) by Neddermeyer and Anderson, Street and Stevenson (I. I. Rabi later asked, "Who ordered that?").

1938 .... Nuclear fission of uranium observed (Otto Hahn, Fritz Strassmann, Ottto Frisch, Lise Meitner).

1939 .... Muon decay observed (Bruno Rossi).

1945 .... First nuclear weapons detonated.

1946 .... Big Bang theory proposed (George Gamow, named by Hoyle later to mock it).

1947 .... Discovery of pion and pion decay in cosmic rays (Perkins, Lattes, and others). Discovery of V particles in cloud chambers at Manchester (George Rochester and Clifford Butler) (now called *kaon* and *lambda*). Lamb shift measured (hydrogen fine structure) (Nobel Prize, 1955).

1948 .... QED developed by Richard Feynman, Julian Schwinger, and Sin-Itiro Tomonaga (Nobel Prize, 1965). Pions produced in accelerators (Berkeley synchrotron).

1949 .... Kaon decay observed (Brown et al.). Spark chamber invented (J. W. Keufel).

1950 .... Neutral pion and its decay discovered (Bjorklund, Panofsky, and Steinberger).

1952 .... Delta particle discovered (Anderson and Fermi). Bubble chamber invented (Donald Glaser). Brookhaven cosmotron accelerator opens.

1953 .... Associated production (later understood as strange particles) observed.

1954 .... First "gauge theory" with charged force carriers (C. N. Yang and Robert Mills).

1956 .... Anti-proton discovered (Berkeley bevatron). Anti-neutrinos from reactors observed (F. Reines and C. Cowan, Nobel Prize, 1995, shared with Martin Perl). Strangeness proposed (Murray Gell-Mann and Kazuhiko Nishijima). Parity violation predicted by T. D. Lee and C. N. Yang (Nobel Prizes, 1957).

1957 .... Parity violation observed (C. S. Wu).

1959 .... CERN (in Europe) and Brookhaven accelerator start operations.

1961 .... Kaon "regeneration" observed. Discovery of spin 1 (vector) mesons (rho, omega, eta).

1962 .... Accelerator production of neutrino beams. Muon-type neutrino is a separate flavor (Lederman, Schwartz, Steinberger, Nobel Prize, 1988).

1963 .... Cabibbo theory of weak decays.

1964 .... Quark model introduced (independently) by Murray Gell-Mann and George Zweig (Nobel Prize, 1969, to Gell-Mann). Omega-particle discovered (bevatron). CP violation in K0 decay discovered (James Cronin, Val Fitch, Nobel Prize, 1980). Higgs mechanism proposed (Peter Higgs, Robert Brout, and F. Englert). Color and gluons proposed (Greenberg, Nambu).

1965 .... Cosmic microwave background observed (Arno Penzias and Robert Wilson, Nobel Prize, 1978).

1966 .... Stanford linear accelerator (SLAC) starts operation.

1967 .... Electroweak unification (the *WSG electroweak model*) proposed independently by Steven Weinberg and Abdus Salam, based in part on contributions of Sheldon Glashow (Nobel Prize, 1979).

1968–1969 .... Deep inelastic scattering at SLAC: Bjorken scaling observed, evidence for partons argued by Feynman (Friedman, Kendall, and Taylor, Nobel Prize, 1990). Ray Davis's Homestake experiment first sees solar neutrino deficit.

1970 .... Proposal of charm (Glashow, Iliopoulos, and Maiani: the *GIM* mechanism).

1971–1972 .... Gerard 't Hooft proves renormalizability of electroweak theory (Nobel Prize, 1999).

1972 .... Fermilab begins operations.

1973 .... QCD developed (Gross, Wilczek, Politzer, Fritzsch, Gell-Mann, Leutwyler, Weinberg, and others). Neutrino experiments verify parton = quark (Gargamelle detector at CERN). Neutral weak current observed (Gargamelle detector at CERN). CKM matrix for weak decays (Cabibbo, Kobayashi, Maskawa).

1974 .... J/psi discovered, the "November Revolution" (S.C.C. Ting at Brookhaven, Burton Richter at SLAC, Nobel Prize, 1976). SU(5) grand unified theory proposed (Howard Georgi and Sheldon Glashow) (later shown to be incorrect because of incorrect predictions of proton decay).

1975 .... Charmed baryons discovered. Tau lepton discovered (Marty Perl, at SPEAR, SLAC, Nobel Prize, 1995, shared with Reines). Quark jets seen (at DESY, in Germany).

1976 .... CERN SPS (super-proton synchrotron) starts.

1977 .... Bottom/anti-bottom meson (upsilon) discovered at Fermilab (Leon Lederman). The standard model is now complete.

1978 .... Parity violation observed in neutral current reactions (SLAC).

1979 .... Three jets seen at PETRA (Germany), direct evidence for gluons.

1983 .... Discovery of Z and W bosons at CERN SPS (Carlo Rubbia's group, Nobel Prize, 1984).

1984 .... Superstring theory developed (Michael Green and John Schwarz).

1987 .... Supernova 1987a (detected with visible light and neutrinos!).

1989 .... Z0 copiously produced at LEP and SLC (number of neutrinos = 3).

1990 .... COBE (Cosmic Background Explorer) satellite returns high-precision data on the cosmic microwave spectrum.

1993 .... Gallium experiments confirm the solar neutrino problem. Atmospheric neutrino anomaly discovered in Japan's Kamiokande experiment. Precision Z0 measurements confirm standard model.

1995 .... Top quark discovered at Fermilab.

1996 .... SuperKamiokande neutrino detector begins operations in Japan.

2000 .... Tau neutrino discovered at Fermilab. Cosmic background radiation spectrum results from Boomerang and Maxima.

2002 .... Evidence for neutrino flavor oscillations from SNO detector in Canada.

Glossary

accelerator: Any device that creates high-speed, high-energy particles.

alpha radiation: When a material releases a stream of particles (radiation) that are, specifically, positively charged helium nuclei (two protons and two neutrons bound together). Caused by the strong force.

angular momentum: A quantitative measure of how rapidly objects turn.

antimatter: Particles that are "opposites" in most respects to ordinary particles; for example, an anti-electron has opposite sign of charge and opposite sign "electron number." However, it has the same mass and the same spin. Matter and antimatter will annihilate, producing pure energy.

associated production: The observation that the strong force conserves strangeness number; that is, in a strong interaction in which two particles are produced, if one has strangeness +1, the other will have strangeness –1.

asymptotic freedom: Quarks that are very close (that is, that interact with very high energy) feel almost no strong force. They are "free."

atom: The smallest building block of *chemistry*, an individual particle of an element. Physically, a heavy nucleus with electrons orbiting.

baryon: A strongly interacting particle with half-integer spin, such as a proton or neutron.

baryon number: A conserved quantum number, +1 for any baryon, –1 for any anti-baryon. No known violation of baryon number has yet been observed but is being investigated.

beta decay: When any particle or nucleus transforms to something else via the weak force, in the process, emitting an electron and (anti) neutrino.

beta radiation: When a material releases a stream of particles (radiation) that are, specifically, electrons. Caused by the weak force.

bevatron: A large nuclear accelerator located in Berkeley, CA. The name came from the beam energy, "billion eV," or BeV. (We would now call that a GeV.) This was the facility where, for example, the antiproton was first discovered.

Big Bang: The theory of the cataclysmic start of the universe. A point of infinite temperature and density, from which the universe was born. Currently estimated to be about 12–15 billion years ago.

boson: Any particle with integer spin (0, 1, 2...). Bosons may be in the same quantum state.

bottom quark: A heavy quark, in the "third generation," similar to a down quark (charge –1/3) but heavier.

broken symmetry: A symmetry of nature that has been hidden by accidental circumstance. For example, a magnet has a direction, even though the underlying forces are truly and precisely symmetrical. The direction is arbitrary, but once chosen, the underlying symmetry is broken and no longer apparent.

Brownian motion: The random "drunken walk" motion of tiny particles (e.g. pollen grains) drifting in a fluid. Observed by Brown in the 1800s, explained quantitatively by Einstein in 1905 as evidence of tinier (invisible) atoms bumping into the grains.

bubble chamber: A device to track charged particles (passing particles ionize a liquid, forming bubbles). Invented in the 1950s.

CERN: European Center for Nuclear Research; home of the largest, highest energy European accelerator.

charm quark: A heavy quark, in the "second generation," similar to an up quark but heavier. First found in the November Revolution in the form of a c-cbar meson.

cloud chamber: A device to track charged particles (passing particles ionize a vapor, forming droplets). Invented in the early 1900s.

color: The "charge" for the strong force. There are three colors.

confinement: The fact that quarks cannot be removed from hadronic matter. They are permanently connected into "colorless" objects.

conservation law: When some quantity remains unchanged during an interaction. For example, charge conservation states that the sum of all electric charges never changes in any particle reaction.

cosmic background radiation: Residual evidence of the Big Bang; low-energy (mostly microwave) photon "bath" we live in, which permeates the universe.

cosmology: The field of physics that studies the structure and evolution of the universe.

CP violation: A symmetry of nature that is slightly broken, effectively a "matter-antimatter" symmetry that is not exactly perfect. A topic of great current interest but not yet well understood or explained.

cyclotron: An older type of particle accelerator.

dark matter: Something that is present throughout much of the universe, carries mass, but does not emit visible radiation; therefore, we don't know what it is. Current estimates are that much of the universe is dark matter!

decay: When a particle transforms, emitting some other lower mass particles as a result. For example, a neutron decays in roughly nine minutes, emitting a proton, electron, and neutrino.

DESY: German high-energy accelerator facility.

detector: Any device designed to identify and characterize the properties of particles.

DIS (Deep Inelastic Scattering): Ultra-high energy particle experiments begun in the 1970s at SLAC. Deep means "very high energy;" the incident electrons come in and go deep into the heart of the nucleus. Inelastic means they give up much of their energy, rather than bouncing, like a rock smashing through a glass window. DIS gave us the first direct evidence for the existence of quarks inside protons and neutrons.

down quark: One of the two light quarks, with spin 1/2 and charge –1/3. (The proton is two ups and a down; the neutron consists of two downs and an up.)

eight-fold way: An early theoretical model to explain regularities in the particle zoo, invented by Murray Gell-Man in 1964. It was the precursor to the idea of quarks.

electroweak theory: The unified quantum field theory of electromagnetism and the weak force. Coined by Salam; developed by Weinberg, Salam, and Glashow.

emulsion: An old, fairly simple detector technology, effectively just like photographic film.

eV: A unit of energy. 1 eV = 1.6×10^{-19} joules. It is a typical "atomic" energy scale.

family: Another name for a generation of particles; for example, the up and down quarks form the lightest family of quarks.

femtometer: A metric unit of distance, 10^{-15} meters; about the size of a proton. Abbreviated fm; sometimes called a "Fermi."

Fermilab: Highest energy accelerator operating in the United States; location of the Tevatron ring; accelerates protons and anti-protons.

fermion: Any particle with half-integer spin (1/2, 3/2, and so on), such as electrons, protons, quarks, and others.

Feynman diagram: Symbolic shorthand for quantum field theory calculations that resembles a "cartoon sketch" of the particle reaction.

field: The physical manifestation of a force of nature, present throughout space; an alternative way of thinking about forces as opposed to "action at a distance."

flavor: The name for the characteristic that distinguishes certain groups of otherwise similar particles. For example, there are three flavors of neutrino: electron type, mu type, and tau type.

force carrier: A particle which serves as the intermediary for a force of nature. For example, the photon is thought of as a particle, a tiny quantum bundle of energy which allows one charged particle to "feel" another one electromagnetically. The photon is then the electromagnetic force carrier.

gamma radiation: When a material releases a stream of high-energy electromagnetic waves (radiation) of very short wavelength.

gauge boson: The force carrier particle in any quantum field theory, such as the photon in QED, the gluon in QCD, and the W and Z in the electroweak theory.

gauge symmetry: An abstract symmetry of nature present for the three fundamental forces (strong, electromagnetic, and weak). The presence of gauge symmetry in a theory requires the existence of mass-less gauge bosons.

general relativity: Einstein's theory of gravity. Not yet consistent with quantum mechanics but spectacularly successful in all experiments to date.

GeV: A billion eV's, 10^9 eV. (See eV.)

gluon: The gauge boson (force carrier) of the strong force.

grand unification: The idea that, at very high energies, all forces of nature (strong, electromagnetic, weak, and ultimately, gravity) become one. They are different low-energy manifestations of one fundamental force. Not yet an established theory.

GUT: A theory of grand unification.

hadron: Any particle that interacts strongly. (Any object made up of quarks.)

Heisenberg uncertainty principle: A fundamental principle of quantum mechanics that certain observables (e.g. position and momentum) are intimately connected: the better you measure one of these quantities, the more uncertain the other must be. It's a quantitative statement of the idea that observations must affect the system being observed.

Higgs mechanism: The mathematics that makes the Higgs field special, breaking the electroweak symmetry, giving the W and Z bosons mass.

Higgs particle: The physical manifestation of the Higgs field; the last unproven piece of the standard model. Actively being sought.

interaction: A synonym for *force*; a way in which particles transform or perturb one another. For example, the weak interaction causes beta decay.

J/psi: The particle found in the November Revolution of 1974, a charm/anti-charm meson. Simultaneously discovered at SLAC and Brookhaven. The particle that in some ways clinched the quark model in many physicists' minds.

kaon: A strange meson (see strangeness, meson); heavy relative of the pion.

Lamb shift: A tiny splitting in the light emitted by hydrogen atoms, indicative of subtle QED effects. The experimental push in 1947 to make QED a successful theory.

lepton: A class of spin 1/2 particles that do not interact strongly. The electron, muon, tau, and the three flavors of neutrinos are all the leptons.

meson: Any strongly interacting particle with integer spin. A bound state of quark and anti-quark. Lightest example is the pion.

MeV: A million eV's, 10^6 eV. (See eV).

molecule: A chemical building block that is not fundamental but built up out of a bound state of two or more atoms, such as an H_2O (water) molecule.

muon: A fundamental lepton, in the "second generation"; a heavy version of the electron. (I. I. Rabi asked, "Who ordered that?") Decays weakly into electron, mu-neutrino, and electron/anti-neutrino.

neutrino: A fundamental lepton, with (near) zero rest mass and zero charge. Interacts only weakly. It is under intense current investigation, because it is not known what the mass is or whether the three different flavors can oscillate from one to the other.

neutrino oscillation: When one flavor of neutrino spontaneously (through quantum mechanics) changes into a different flavor. Under current study at many facilities, this is not a part of the standard model.

neutron: Partner of the proton, electrically neutral baryon that is present in essentially all nuclei. Consists of d, d, and u quark.

Noether's theorem: A beautiful and important mathematical theorem relating symmetries of physical theories with conserved qualities.

November Revolution: The discovery of the J/psi particle in November 1974.

nucleon: A generic name for neutrons and protons, the "constituents of nuclei."

nucleus: A bound collection of protons and neutrons; the center of atoms.

parity: Mirror symmetry; the observation that the laws of physics are the same when viewed in a mirror.

parity violation: The breaking of parity symmetry. Only the weak interaction violates parity; for example, the weak interaction will produce "left-handed" particles but not "right-handed" ones in some reactions.

particle physics: The study of the fundamental constituents of nature and their interactions with one another.

Pauli exclusion principle: A quantum mechanical law stating that identical fermions cannot be in the same quantum state at the same time. This principle is responsible, in a very real sense, for much of chemistry.

periodic table: Mendeleev's organization of atoms into a simple "table," in increasing order of weight, which shows the underlying structure of atoms.

photoelectric effect: Explained by Einstein in 1905; when light hits a metal, it can eject electrons. The details can only be understood by postulating some "particle-like" properties to the light.

photon: The spin-1 gauge boson of electromagnetism, the quantum of light, the carrier of the electromagnetic force.

pion: Originally postulated by Yukawa as the carrier of the strong force, it is now simply the lightest meson, a spin-0 quark/anti-quark bound state. Comes in +, –, and zero charges; the charged versions decay weakly into a muon and muon neutrino.

positron: An anti-electron (see antimatter).

proton: The fundamental baryon, building block (with neutrons) of nuclei. Composed of two ups and a down. A stable particle as far as we know (still under investigation, but if it decays, the lifetime is very long).

QCD: Quantum chromodynamics, the quantum field theory describing the color force, the strong interaction between quarks.

QED: Quantum electrodynamics, the quantum field theory describing the electromagnetic force.

quanta: Chunks, of just about anything.

Quantum chromodynamics: See QCD.

Quantum electrodynamics: See QED.

quantum mechanics: The physical theory which tells how microscopic particles behave under the influence of forces.

quantum numbers: Properties of elementary particles that come in chunks; for example, the quantum numbers of a proton are: charge 1, strangeness 0, baryon number 1, lepton number 0, and so on.

quark: The fundamental spin 1/2 constituents of all strongly interacting objects. Quarks come in six flavors: u, d, s, c, t, b (up, down, strange, charm, top, bottom). Never found isolated; they always come as q-qbar (meson) or q q q

(baryon). Quarks carry electric charge and color charge and experience all fundamental forces of nature (but the strong force generally dominates). The heavier quarks are not stable.

reductionism: The philosophical principle that complex systems can be understood once you know what they are made of and how the constituents interact.

relativity: Generic term usually reserved for Einstein's theory that describes the motion of particles moving at high speeds. Modifies our conventional views of space time and gravity. (It does not mean that "everything is relative.")

renormalizable: A quantum field theory that can be easily fixed up to yield finite results.

renormalization: A mathematical technique to take a quantum field theory, which generally produces infinite results, and "fix up" a *small* number of formal "bare" quantities so that, after adding the infinite quantum corrections, you match experimental data in the end. Once you do this for the small number of quantities, every other observable is then finite and well determined.

RHIC: Relativistic Heavy Ion Collider. A nuclear physics accelerator in Brookhaven, NY, just recently opened. Produces high-energy, heavy particles to make high-density, high-temperature collisions.

SLAC: Stanford Linear Accelerator Center. A two-mile-long electron accelerator, now up to a maximum of almost 100 GeV. Extremely successful and long-lived accelerator.

solar neutrino: A neutrino emitted from the nuclear reactions in the core of the sun. Generally very low in energy, but there are a lot of them.

solar wind: A constant stream of energetic particles emitted by the sun.

special relativity: Einstein's 1905 theory describing the motion of particles moving at high speeds. Modifies our conventional views of space and time. (*Special* means the theory is limited to observers moving with steady velocity and ignores gravity.)

spin: A quantum property of particles. It is somewhat analogous to "rotational angular momentum," how fast something is spinning, but applies even to point particles. Spin is quantized. Particles can have spin 1/2, 3/2, 5/2, and so on (fermions) or 0, 1, 2, and so on (bosons). (Those numbers are really expressed in units of h/2 pi, where h is Planck's constant, 6.63×10^{-34} Joule × sec.) Spin can also be thought of as describing degrees of freedom of a particle; for example, spin 1/2 particles have two degrees of freedom (up or down).

SSC: Superconducting Supercollider, the failed U.S. mega-project that would have produced protons at extreme energies to search for the Higgs and learn about electroweak symmetry breaking.

standard model: The theory of fundamental particles. It consists of a list of the particles and their properties (the quarks and leptons and the Higgs, their charges and masses) and the theories that describe their interactions, specifically, QCD and the electroweak theory.

strange quark: A second-generation quark, charge –1/3, heavy relative of the down quark.

strangeness: A quantum number of hadrons that effectively just counts how many strange quarks are in the object (times –1, technically). Strangeness number is conserved by all forces except the weak force.

string theory: A tentative fundamental theory of nature in which particles are described not as points, but as tiny strings, living in ten (or more) dimensions. This theory appears to give finite results, unifies all four forces, leads to general relativity, and may also yield the standard model as its "low-energy limit." Under active investigation as the ultimate theory of nature; stay tuned.

strong interaction: One of the four known fundamental forces; binds quarks together. (May also refer to the residual force that binds protons and neutrons together.) Responsible for alpha decays.

superconductor: A metal that conducts electricity with zero resistance. Used to make ultra-powerful magnets; needed in high-energy accelerators to bend particles.

supersymmetry: A hypothesized additional symmetry of nature that relates fermions and bosons. Not yet experimentally verified. If supersymmetry exists, every particle should have a supersymmetric "partner," probably heavier, differing by 1/2 unit of spin. Supersymmetric partners of fermions are named by adding an *s* in front

(selectron, squark, and so on), while partners of bosons are named by adding an *ino* on the end (photino, gluino, Wino, and so on).

symmetry: When a system appears unchanged after some specific change is made to it (such as rotating a cube by 90 degrees or replacing a proton with a neutron in a strong interaction).

synchrotron: A circular accelerator using electric fields to speed up charged particles and magnetic fields to make them travel in a circular path. A synchrotron is designed to handle even relativistic particles.

tevatron: The name for the latest accelerator facility at Fermilab, in Chicago. TeV stands for “Terra-eV” or “trillion electron volt,” a measure of the highest energies the protons in the ring can achieve. This is the facility where the top quark and tau neutrino were discovered.

TOE: Theory of Everything. The dream of particle physicists, an ultimate theory that unifies all four fundamental forces and all particles. String theory is a candidate. It is still only a theory of subatomic particles, so the name is misleading. You will not be able to figure out tomorrow’s weather any better with a TOE.

top quark: The most massive quark of all, the third-generation partner of up and charm. Found at Fermilab in 1995 but predicted and expected since 1975.

translation symmetry: The symmetry of nature which states that the laws of physics are the same at any place in the universe. (Think of “translation” as meaning “moving sideways.”) This does not say that conditions are the same—clearly the inside of the sun is hotter than my house, but the laws of nature are still the same there.

unification: The goal of physicists to find a deep connection between forces. Electricity and magnetism were unified by Maxwell in the 1860s; they are both manifestations of one underlying “electromagnetic field.”

up quark: One of the two light quarks, with spin 1/2 and charge +2/3. (The proton is two ups and a down; the neutron consists of two downs and an up.)

vacuum fluctuations: The vacuum refers to empty space. Even in empty space, quantum mechanics allows for the bizarre possibility that particle anti-particle pairs can spontaneously spring into a tenuous, “virtual” existence for a brief time before re-annihilating into nothing. The bubbling background, which exists everywhere, is called “vacuum fluctuations.”

Van de Graaff accelerator: One of the earliest particle accelerators, this device built up very high voltages (in order of 1 million volts). Often seen today in science museums and physics lecture demonstrations.

W or W-boson: A carrier of the weak force. W’s are electrically charged; for example, a neutron can decay into a proton and a W-boson. The W-boson then decays into an electron and an electron anti-neutrino. Weighs about 80 times as much as a proton.

weak boson: A generic term for the W’s and Z’s.

weak interaction: One of the four fundamental forces of nature, responsible for beta decay, and the only force that neutrinos feel. All particles feel the weak interaction.

x-rays: High-energy electromagnetic radiation. Often used as a synonym for gamma rays, although x-rays connote slightly lower energy radiation.

Z, or Z-boson: A carrier of the weak force. Z’s have no electric force; they transmit the “weak neutral current.” For example, when a neutrino scatters from another particle, it can emit a (virtual) Z particle, much like an electron scatters by emitting a (virtual) photon. Weighs about 90 times as much as a proton.

Particle Physics for Non-Physicists—A Tour of the Microcosmos

Part II

Professor Steven Pollock

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Steven Pollock, Ph.D.

Associate Professor of Physics, University of Colorado, Boulder

Steven Pollock is associate professor of physics at the University of Colorado, Boulder. He did his undergraduate work at MIT, receiving a B.Sc. in physics in 1982. He holds a Master's and a Ph.D. in physics from Stanford University, where he completed a thesis on "Electroweak Interactions in the Nuclear Domain" in 1987. Professor Pollock did postdoctoral research at NIKHEF-K (the National Institute for Nuclear and High Energy Physics) in Amsterdam, Netherlands, from 1988–1990 and at the Institute for Nuclear Theory in Seattle from 1990–1992. He spent a year as senior researcher at NIKHEF in 1993 before moving to Boulder.

Professor Pollock's research work is on the intersections of nuclear and particle physics, with special focus on parity violation, neutrino physics, and virtual strangeness content of ordinary matter. Professor Pollock was a teaching assistant and tutor for undergraduates throughout his years as both an undergraduate and graduate student. As a college professor, he has taught a wide variety of university courses at all levels, from introductory physics to advanced nuclear and particle physics, including quantum physics (both introductory and senior level) and mathematical physics, with an intriguing recent foray into the physics of energy and the environment. Professor Pollock is author of *Thinkwell's Physics I*, a CD-based "next-generation" multimedia textbook in introductory physics.

Professor Pollock became a Pew/Carnegie National Teaching Scholar in 2001 and is currently pursuing classroom research into student attitudes toward physics in large-lecture introductory courses. He received an Alfred P. Sloan Research Fellowship in 1994 and the Boulder Faculty Assembly (CU campus-wide) Teaching Excellence Award in 1998. He has presented both nuclear physics research and his scholarship on teaching at numerous conferences, seminars, and colloquia. Professor Pollock is a member of the American Physical Society, Nuclear Physics Division, and the American Association of Physics Teachers.

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Particle Physics for Non-Physicists—
A Tour of the Microcosmos

Scope:

The buzzwords appear with regularity in newspapers and magazines—*quarks*, *neutrinos*, the *Higgs boson*, *superstrings*... It's the lingo of particle physics, the study of the deepest, most fundamental constituents and interactions of the physical world. This course will offer a tour of the particle zoo and the ideas and phenomena involved in qualitatively understanding current concepts of modern physics. No math involved! What's so strange about strange quarks? Why didn't we build a superconducting supercollider? Should we believe in particles that no one has ever seen—and never will? We'll learn about the most fundamental constituents of nature and the forces they feel—the history and discoveries, the apparatus and ideas, some of the curious characters involved, and the research and mysteries that are still being pursued today.

We begin on a fairly historical track. From the ancient Greek philosophers, we jump to Renaissance scientists whose work formed the starting point of physics. The scientific method developed by Isaac Newton more than 300 years ago continues to serve us well. Many of the physical insights Newton had, although now deepened and improved by modern physics ideas, are still relevant for understanding how the world works, which is the goal of this course and, indeed, of all physics. We jump again, to the start of the twentieth century, when new discoveries forced a radical shift in thinking about the behavior of matter—the dawn of quantum mechanics. We will not cover (or assume) any detailed knowledge of these laws of physics, discussing only the key ideas we need for the rest of this course. A "classical" approach to particle physics, although not technically correct, will serve us quite well. Students will find that understanding the basic elements of particle physics using common sense and classical intuition is possible, provided that we keep our minds open for the occasional quantum weirdness!

We will follow the early developments, both theoretical and experimental, and see how they lead us to an organizing scheme for matter at the smallest possible scale. The idea of seeking the fundamental constituents and the forces they feel will guide us through the rest of the course. We will learn about the growing "particle zoo," with just enough vocabulary to talk sensibly about the fundamental objects discovered from the early 1900s up through the most recent findings. This will lead us to quarks and neutrinos, force carriers and Higgs bosons, squarks and Zinos. Along the way, we will learn qualitatively about the theories required to describe such creatures—quantum fields, virtual particles, and all!

All this leads to what is now known as the *standard model of particle physics*—really the standard *theory*—a complete and self-consistent description of the apparently fundamental, point-like building blocks of everything, their interactions with one another, and the "rules of the game." We then move to more modern questions: Do we really have a fundamental theory at hand? Does that question even make sense? What is going on today in the world of particle physics? What are the central issues? What's hot these days? As we move through the course we will continually ask ourselves two key questions: Why is this idea interesting, and how do I know that it is true? Both are at the heart of appreciating science.

Lecture Thirteen

Symmetry and Conservation Laws

Scope: What does the word *symmetry* mean to a physicist? Almost what it means to you: an aesthetic property of a system, a pattern that appears the same when viewed from a different perspective. The role of symmetry in our understanding of the universe has evolved considerably with time to become a guiding theme of physics. Emmy Noether's theorem played some role in this development; we'll learn how she connected symmetry to *conservation laws*, which are of enormous practical value. Spatial symmetries are easy to picture, but the more abstract, "internal" symmetries are not. How do we work these into a theory? What do they tell us about the world? Why are physicists so enthralled with symmetry?

> Symmetry seems to be absolutely fascinating to the human mind. We like to look at symmetrical things in nature, such as perfectly symmetrical spheres like planets and the sun, or symmetrical crystals like snowflakes, or flowers which are nearly symmetrical. However, it is not the symmetry of the objects in nature that I want to discuss here; it is rather the symmetry of the physics laws themselves.
>
> —Richard P. Feynman (*The Character of Physical Law*, chapter 4)

Outline

I. In the next two lectures, we turn from the constituents to the laws of physics and the tools that physicists use to understand how the world works. One of the most powerful of these is the principle of symmetry.

- **A.** The meaning of the word *symmetry* in physics is fairly close to the meaning that you might think of but a bit more general. To a physicist, *symmetry* relates to looking at an object or a system from a different perspective. If an object looks the same from two different perspectives, then we say that it is symmetrical.
- **B.** A snowflake has six-fold symmetry, which means that if it is rotated by one-sixth of a turn, it looks the same as it did at the start.
- **C.** We can also talk about more abstract symmetries. If we say that a mathematical theory has symmetry, we mean that even if we make some change in perspective, the answers remain the same.
- **D.** The mathematics of symmetry is called *group theory* and was once obscure. We now think of it as simply the mathematical formalism that describes the different kinds of symmetries that exist in the world.

II. Let's begin by looking at some perfect symmetries.

- **A.** Imagine that you see a group of children on a field playing some sort of game. Some of them are wearing green shirts and some are wearing red shirts. What is the nature of their game? You might try to answer that question in a number of ways.
  1. If all the children change into green shirts and continue to play in the same way, you learn that the game has symmetry, because a change in color is completely irrelevant to the rules.
  2. This fact teaches you something about the game; that is, it probably doesn't involve teams. You don't know everything about the game, but symmetry is one tool that helped you learn one aspect.
  3. If the children change shirts, then don't know what to do, you learn that the game probably does involve teams, and that color matters. Lack of symmetry has taught you something about the game.
- **B.** That analogy was a bit of a stretch, but it is a good one for a discussion of the strong nuclear force, which involves protons and neutrons combining to form a nucleus.
  1. Remember that in the 1930s, scientists were trying to understand the strong nuclear force. As in the game analogy, they discovered that the label "proton or neutron" was irrelevant. The forces of attraction held true whether the particles in question were protons or neutrons.
  2. In other words, protons attract protons, protons attract neutrons, and neutrons attract neutrons. There was no change in the rules when the nature of a particle was changed from proton to neutron.
  3. The strong force has a proton/neutron symmetry, which taught us something about the nature of protons and the nature of the strong force. Later, we came to understand that this force was further explained by the existence and nature of quarks.

C. What does symmetry teach us? In this case, we learned something about the nature of the nuclear force. Symmetry simplified our worldview. It reduced the number of degrees of freedom that we had to account for in describing a nucleus mathematically.

D. Think back to the snowflake example, which is geometrical. If we rotate a snowflake by 60 degrees, it looks the same. That fact teaches us something about the crystals that build the snowflake; in this case, we learn something about what goes on inside the structure.

III. We can also look for symmetry in theories, such as in Emmy Noether's mathematical theorem of symmetry and conservation laws from 1915.

A. Emmy Noether was raised and lived most of her life in Germany in the late 1800s through the early 1900s—a difficult time for a woman to be a mathematician. She met many challenges in her life to get her Ph.D. in mathematics and secure a position at a university.

B. Noether developed a theorem to connect symmetry to conservation laws. Generally, it argues that if we have a specific symmetry, then we are guaranteed to have a conservation law associated with that system.

1. Remember that a conservation law says that if we start with some quantity and it undergoes any number of changes, in the end, we will still have the same original quantity.

2. For example, if we start with some energy, we might change its form or create matter/antimatter, but we will always have the same total energy in the end. The same is true of electric charge.

C. Noether's theorem connected an abstract principle of a theory, its symmetry, to a practical benefit. Let's look at some specific examples.

1. Imagine that I am doing a physics experiment in which I knock billiard balls against one another to tabulate the laws of physics.

a. If I do the same experiments in a different location, the laws of physics are the same. The laws are unchanged when the system is viewed from a different perspective, which is the definition of symmetry, in this instance, *translational symmetry*.

b. Noether's theorem states that every symmetry of nature has an associated conservation law. We can't guess what will be conserved, but we can use the theorem to derive it.

c. We discover that translational symmetry leads to conservation of momentum. If an object is moving to the right and it crashes into something, whatever is left of the object after the crash will still have some motion toward the right.

d. Knowing about translational symmetry and conservation of momentum, we can test these ideas in the laboratory. How far can I take my equipment and still have the laws of physics be the same? As far as we know, the laws of physics operate the same as they do here even in the Andromeda Galaxy.

2. If I do my experiments today, then I do them tomorrow, I also find that the laws of physics are the same. This symmetry is *time translation*. At different times—which would be from a different perspective—the laws of physics are the same. The conservation law associated with time translation is conservation of energy.

IV. Let's discuss one more symmetry of nature that is very abstract and ties in with Noether's theorem—*gauge symmetry*.

A. Gauge symmetry arose in the theory of electricity and magnetism. In the 1800s, people observed that the laws of electricity and magnetism were symmetrical. They were invariant under a certain change.

1. Think of a simple electrical circuit. If we have a car battery and some wires going to a light bulb in the headlight of the car, when we hook them up, the light bulb glows.

2. The laws of electricity and magnetism allow us to make predictions about how bright the bulb will be, how long it will burn, how hot the wires will become, and so on. These are consequences of the laws of electricity and magnetism.

3. To do the calculations to make these predictions, we need to know that one side of the battery is at 0 volts and one side is at 12 volts. Physicist A does his calculations from the premise that the left side of the battery is at 0 volts and the right side is at 12 volts. Physicist B does her calculations from the premise that the left side of the battery is at 12 volts and the right side is at 24 volts. The numbers are different, but the difference is 12.

4. **4.** Does Physicist B come to the same conclusions about the observables as Physicist A? The answer is yes. It's completely irrelevant what numerical value is assigned to the left pole and the right pole; all that matters is the difference.
5. **5.** That's the essence of gauge symmetry: No matter what point is picked to be 0, the results are the same.

B. The conservation law associated with gauge symmetry is conservation of electric charge, which is quite useful in a wide variety of experiments, not just those in particle physics.

V. We'll conclude this lecture by returning to the development of QED.

A. Remember that Feynman, Schwinger, Tomonaga, and others were trying to come up with a quantum mechanical theory that would take into account the nineteenth-century understanding of electricity and magnetism and make it consistent with quantum mechanics.

B. These scientists already knew that their quantum theory must obey the law of gauge symmetry.

C. To ensure that the quantum theory was gauge symmetric, the mathematics forced scientists to introduce a new particle of nature, the photon.

1. **1.** The photon comes out of the *principle of gauge invariance*, which is another term for *gauge symmetry*.
2. **2.** All the properties of the photon also follow from the requirement that the theory be gauge symmetric.

D. Once we have a gauge symmetry that we believe is present in nature, we can start to predict not only the existence of particles, but their properties.

E. In later years, when people began thinking about the strong force between the quarks, the color force in QCD, they didn't have an earlier understanding to work from. They had to create the theory from scratch, and they used gauge symmetry as a guiding principle.

F. These scientists started from the idea that if gauge symmetry is true for electricity and magnetism, it might also be true for the color force. Further, if gauge symmetry is true for the color force, then there must be a particle of nature that carries the strong force. We now call this particle the *gluon*, and we know that it has certain properties, which all come out of the theory.

G. Even later, when scientists were trying to understand the weak force of nature, which was even more complicated, they again asked if it was related to gauge symmetry and again predicted the existence of a particle. This particle, the carrier of the weak force, is the Z particle.

Essential Reading:

Weinberg, *Dreams of a Final Theory*, chapter VI.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 5.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 10.

Recommended Reading:

Krauss, *Fear of Physics*, chapter 5, first half, up to "Symmetry breaking."

Greene, *The Elegant Universe*, pp. 124–126.

Lederman, *The God Particle*, chapter 7, section on "Conservation laws."

Calle, *Superstrings and Other Things*, chapter 25, first half, up to "The color force."

Wilczek and Devine, *Longing for the Harmonies*, Eighth Theme (through chapter 25).

Questions to Consider:

1. The laws of physics have many invariances; for example, they are the same no matter what your position is in the lab or what time it is in the lab. Are there more?
   (a) Do the laws of physics change depending on your orientation in the lab, that is, which way you are facing?
   (b) Do the laws of physics change depending on your speed as you walk across the lab, assuming that you walk in a straight line with a steady speed?
   (c) Do the laws of physics change depending on whether you sit still or accelerate across the lab? (This is a subtle one!)
2. Do you agree with the U.S. Patent Office policy that perpetual motion machines (which explicitly violate energy conservation) should be dismissed out of hand, without any further investigation? Why or why not?
3. Can you think of a symmetry in the world of particle physics that is exact? How about one that is approximate but not exact?

Lecture Fourteen

Broken Symmetry, Shattered Mirrors

Scope: Imperfect symmetry is called *broken symmetry*, which can be either slight or extreme. In either case, we inevitably learn something useful about the world. What is *mirror symmetry* (also called *parity*), and what would it mean if it were broken? We look at the surprise of parity violation and the role of broken symmetry in modern particle physics. This topic is difficult but significant to particle physics; we will accept some confusion without ending our exploration.

> I heave the basketball; I know it sails in a parabola, exhibiting perfect symmetry, which is interrupted by the basket. It's funny, but it is always interrupted by the basket.
>
> —Michael Jordan (former Chicago Bull)

> A broken symmetry breaks your heart.
>
> —Abdus Salam (*The World Treasury of Physics, Astronomy, and Mathematics*, p. 669)

Outline

I. In the last lecture, we noted that symmetry can serve as a simplifying principle. If we find that a complicated system is symmetrical, our description and understanding of the system can be made easier. We can also make predictions using symmetry, as we did with Noether's theorem and the laws of conservation.

- **A.** In the real world, many times, symmetry is broken. Consider your own body. Are your hands the same? In some respects, yes, but in other ways, no. You can't put a right glove on a left hand, for example.
- **B.** Think again about watching children play a game, this time, soccer. The team of boys is wearing blue uniforms, and the team of girls is wearing pink. If we have the teams switch uniforms, we should find that an exact symmetry exists between uniform colors.
  - **1.** Suppose that after watching many games, we observe that the pink team seems to win more often. That's a breaking of symmetry.
  - **2.** We might conclude that in America, young girls mature faster than boys and tend to be more coordinated and stronger. Thus, the pink team may beat the blue team more often if they're second graders, but not when they're tenth graders.
  - **3.** This subtle breaking of symmetry teaches us something about the players and the culture they live in.
  - **4.** If the players are high school students and the boys are forced to wear pink, the girls might laugh at them and the game might fall apart. This is a more radical breaking of symmetry. We didn't expect to swap the two colors and stop the whole game.
- **C.** Physicists often look at systems first for symmetry, which is easy to find when the symmetry is exact or almost exact. Often, if we find a slight break in symmetry, we notice it and it teaches us something.
  - **1.** For example, as we've noted, the laws of the strong interaction are independent of whether a particle in a nucleus is a proton or a neutron. This is a deep symmetry of nature, but it's not exact.
  - **2.** A nucleus with a proton and a neutron is stable, but one with two protons is not. Swapping a neutron for a proton changes electrical properties. Because electricity is very weak compared to the strong force, it doesn't have a big influence, but it can play a role.
  - **3.** We can point to another symmetry between protons and neutrons that is also broken, very subtly: If they were completely symmetrical, they would weigh exactly the same, but a neutron weighs about 0.1 percent more than a proton.
  - **4.** This breaking of symmetry teaches us that the down quark might have a slightly different weight than the up quark. After all, a neutron is made of two downs and an up, and a proton is made of two ups and a down. A tiny difference between the quarks, then, could lead to a tiny difference between the two objects.
  - **5.** We can also use this breaking of symmetry to learn something about electricity. At first, we might say that the role of electricity inside a nucleus is insignificant. The strong force binds everything together tightly.
  - **6.** However, electricity exists inside the nucleus. Positive charges repel, but the neutrons are not repelled, because they're neutral. Again, we learn about the connection between electricity and the strong force

in the nucleus by looking at the differences between nuclei that have different numbers of protons and neutrons.

II. We also need to look at some situations in which symmetry is so badly broken that we hardly recognize it ever existed.

A. For example, imagine that you're at a fancy dinner and you sit down at a large, round table. In front of each seat is a plate and in between the plates is a glass of water.

1. When you sit down, there's a glass of water on your left and a glass of water on your right. You might think that because the table is perfectly symmetrical, you are free to choose either glass.

2. Sooner or later, however, somebody around the table will reach for a glass. If the first person picks up a glass with his or her left hand, the symmetry is broken. You no longer have a choice.

3. A latecomer might arrive and see a full glass on the left and an empty glass on the right. This latecomer believes that the table has no symmetry.

B. Let's look at another example that is more related to physics.

1. Suppose you look inside a kitchen magnet. Physicists understand magnetism as arising from the magnetism of individual atoms, but let's just take for granted that an individual atom acts like a tiny magnet with a north pole and a south pole.

2. The atom can be oriented in any direction, and if it's warm, it moves around. First, it points north, then west, then east.

3. Now suppose that you have a crystal, which is a large number of atoms. If all the atoms are pointing in different directions, the result is just a crystal, not a magnet.

4. What happens if all the atoms in the crystal are magnetized in the same direction? If the atoms are pointing in opposite directions, they cancel, but if they're pointing in the same direction, they add up. Thus, a kitchen magnet is a material in which all the atoms are pointing in the same direction.

5. Let's think a little bit more about why this happens. If you warm up your kitchen magnet, it will demagnetize, because the thermal energy results in the atoms pointing in different directions. If you cool it down, the atoms will tend to begin lining up again in a sort of chain reaction, and the magnet will remagnetize itself.

6. A tiny physicist living inside the magnet might deduce that north and all the other directions of the compass are radically different, because all his experiments tend to point toward north. He might conclude that the laws of nature are not symmetrical. If another tiny physicist comes along and heats up the world around them, she could prove that their world has broken symmetry, but that the laws of nature do not.

C. Let's go back to mirror symmetry, in which you notice that your left hand and your right hand are nearly the same, but they're opposite. Physicists call mirror symmetry *parity*, or *p symmetry*.

1. Remember that a human body is almost, but not quite, left/right symmetric, but that's not a law of nature. A human body is an object.

2. The breaking of symmetry of a human doesn't break any symmetry of laws of nature.

D. To further understand this idea, imagine that you are using a pool table to do physics experiments in a room that has a big mirror on the wall. Instead of watching the table, however, you watch the mirror and take all your data from the mirror-image balls.

1. When you watch the laws of physics in a mirror world, you find that they are exactly the same as they are in our world. You could check electricity, magnetism, and the strong nuclear force, and you would find that the outcomes are identical but reversed in the mirror and on the pool table.

2. Any physicist would agree that the laws of physics are unchanging with time or space. In fact, in 1956, two physicists, Lee and Yang, wrote a paper in which they observed that this fact of mirror symmetry had been verified countless times for gravity, electricity, magnetism, optics, and the strong nuclear force.

3. But nobody had ever checked the weak interaction. What if we look at a beta decay? That's a weak nuclear reaction. Is it true that the reaction and its mirror reaction both occur with the same probability in the real world? Lee and Yang posed this question.

4. Of course, most physicists believed that parity symmetry would be unbroken. A year later a physicist named C. S. Wu set up an experiment to test mirror symmetry.

a. Let me try to summarize the idea for you: If we have a nucleus that is spinning in the clockwise direction, we might say that it has a certain "handedness." If a particle is moving away from me and spinning clockwise, I call it a right-handed particle. Similarly, a left-handed particle would be spinning in a counterclockwise direction from my point of view.
b. Wu examined some nuclei that had a certain handedness and were in beta decay. After the decay, she was left with a nucleus that had been transformed, and beta rays (electrons) go flying out.
c. Imagine watching this experiment in a mirror. If the nucleus in the real world is spinning clockwise, the mirror nucleus is spinning counterclockwise. If the real nucleus is labeled north and south, the mirror nucleus is the opposite, south and north.
d. If the world is mirror symmetrical, we would expect that the outgoing electrons would be equally likely to go north as to go south, or east or west. If all the electrons went north in the real world, that's what we would call south in the mirror world and would be a drastic breaking of mirror symmetry.
e. Wu's experiment found that *almost* every electron goes to the north and none of them goes south. It was almost the maximal breaking of mirror symmetry imaginable.

5. As we know, the weak interaction is already rather odd; it changes the strangeness of particles; it transforms neutrons into protons; and apparently, it knows the difference between something spinning right-handed and something spinning left-handed.
6. Many, many experiments were done after Wu's, and they all verified that in any weak interaction, left-handed spinning particles and right-handed spinning particles behave differently.
7. In fact, when we start doing experiments with neutrinos, we would expect that right-handed and left-handed neutrinos would be equally likely to exist in the universe, but there are no right-handed neutrinos. To an excellent approximation, the neutrino massively breaks mirror symmetry.
8. We have also found that matter/antimatter symmetry is broken, although more subtly than parity symmetry in this instance.

E. In physics, we look at these broken symmetries and ask: Is that an accident, or is there a reason that this symmetry is broken? Does it have some fundamental origins? Can we learn something from it?

Essential Reading:

Weinberg, *Dreams of a Final Theory*, chapter VIII.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 7 (slightly hard going).

Recommended Reading:

Lederman, *The God Particle*, "Interlude C."

Krauss, *Fear of Physics*, chapter 5, second half, after the introduction of "Symmetry breaking."

Wilczek and Devine, *Longing for the Harmonies*, chapter 26.

Questions to Consider:

1. When you look at a mirror image of a map of the United States, it is hardly recognizable. Is this an example of parity violation; that is, does it demonstrate that the laws of physics are not mirror symmetric? Why or why not?
2. Consider an idea from Richard Feynman: Suppose you could have a radio conversation with a distant alien race. We have no visual connection, audio only. The members of this race are so distant that we can't even see the same stars. After much effort, you might learn to communicate with them. (Perhaps you could tap 1, then 2 so that they could understand how we count. Then you might say "hydrogen" and tap 1, then "helium" and tap 4, and so on, tapping the atomic weights of the elements. They might then figure out the names of elements.) Imagine, ultimately, that you could converse freely with them. Then one day, they ask you to describe yourself, and you say, "My heart is on my left side." The aliens reply, "We don't know the word *left*. Which side is left?" Think carefully about this: How could you possibly explain this to them?

   (Hint: If parity was not violated, I don't believe that there is any conceivable way that you could!)

Lecture Fifteen

The November Revolution of 1974

Scope: In November 1974, two simultaneous experimental discoveries rocked the world of particle physics. A new quark had been found. It came from two radically different places—a cutting-edge detector at Stanford and a challenging experiment at a powerful facility in Brookhaven. The new *charmed quark* had been anticipated (at least, by a few) and fit so well into the quark model and the new theory of QCD that it changed the scientific paradigm for many physicists nearly overnight. In some sense, this event was the dividing line between early particle physics and modern high-energy physics.

> The man was tired, for he had diligently worked the area for weeks. He stooped low over the pan at the creek and saw two small glittering yellow lumps. "Eureka!" he cried, and stood up to examine the pan's content more carefully. Others rushed to see, and in the confusion, the pan and its contents fell into the creek. Were those lumps gold or pyrite? He began to sift through the silt once again.
>
> —Harvey Lynch (SPEAR Logbook, Nov. 9, 1974)

> BJ, I think you'd better go down to the lab now.
>
> —James Bjorken's wife (on the evening of the discovery of the psi particle at SLAC)

Outline

I. By the early 1970s, the quark model was definitely established, but it was by no means dogma in the world of physics. As we've said, particle physicists were aware of the model, but many believed that it might be just a mathematical framework, not a reflection of a real object.

- **A.** At the same time, the theory of quantum chromodynamics, the mathematical framework for understanding the strong force, was in development. This theory showed why quarks were not being observed in the laboratory, but it had not been widely disseminated.
- **B.** The experiment that revealed that quarks were physically real occurred in the mid-1970s, at a time now called the *November Revolution*.

II. The November Revolution is a play with two acts. Experiments were going on in parallel at two large experimental facilities in the United States.

- **A.** We'll begin with the facility on the West Coast, the Stanford Linear Accelerator Center (SLAC).
  - **1.** Using this accelerator, electrons are accelerated up to an energy of a couple of billion eV, then smashed into targets.
  - **2.** The physics community had debated whether smashing electrons was productive. Why not accelerate protons? When a proton hits a target, it interacts strongly, but the electron does not.
- **B.** The competing philosophy was manifested on the East Coast by an accelerator at Brookhaven National Lab on Long Island.
  - **1.** This facility accelerated protons up to a much higher energy, closer to 30 billion eV. These experiments produced many more events, because the interactions were strong.
  - **2.** This interaction is also more complicated, because the object being smashed is more complicated and results in much more debris. The interpretation was more difficult on the East Coast.
- **C.** At Stanford, the director of one of the research groups, Burton Richter, had an interesting idea.
  - **1.** Richter knew that when energy is pumped into a small region of space to smash electrons into a target, e+/e– pairs can be produced.
  - **2.** Richter wondered what would happen if the positrons were channeled by some sort of magnetic field and trapped. He proposed accelerating the positrons further and running them in the same circle with electrons. Because they have opposite charges, they would run opposite each other, and at a certain point, they would collide.
  - **3.** The result of this experiment would be, for the first time, matter/antimatter collisions right in front of a detector. The electron and the anti-electron would annihilate. Pure energy would exist for a brief moment, then the energy would be converted into creating new particles of nature.

- **D.** Brookhaven was using its high-energy proton beam to produce large numbers of new particles, including new matter/antimatter pairs.
  1. A physicist there named Samuel Ting was looking at all the debris coming out of the smashed protons to find a muon and an anti-muon coming out back-to-back.
  2. What would make a muon and an anti-muon appear out of this debris? Presumably, they would be created from some small bundle of energy, maybe a particle, for example. Imagine that a particle is created; it lives for a short time, then decays. One of the things that it might decay into would be matter/antimatter.
  3. Muons leave a distinctive signature in a detector. Remember that the muon is like a heavy electron; it does not interact strongly.
  4. In the summer of 1974, Ting's research assistants noticed something interesting in the data. According to conservation of energy, total energy going in must equal total energy going out. As they graphed the data, the researchers noticed a number of events at one particular energy. Many muon pairs were being produced with the exact same total energy. Such an event is now called a *bump*.
  5. This bump indicates, most likely, that there is a fundamental particle of nature with that energy. In this case, it was a very unusual signal for a variety of reasons. Ting understood that he had made a radical discovery of a particle that was super narrow and super strong, but he did not immediately publish his data.
- **E.** On the West Coast, Richter's group now had an e+/e– collider and was analyzing data from a reverse of Ting's experiment. Instead of looking for a particle/anti-particle pair coming out, they were starting with a particle/anti-particle pair, then looking for what was produced.
  1. The procedure is to tune the energy of the beams to know exactly how much energy is coming in to the system, then to look at all the particles that come out; most of the time, not much happens.
  2. If you hit a resonance—the energy where a particle could be created—then you'll create that particle. It will exist for a moment, then it will fall apart and other particles will come out.
  3. Experimenters at Stanford had been steadily ramping up the energies in the accelerator and collecting data. Earlier, some researchers had noticed an unusually high count rate of events in the detector at around 3 billion eV. The decision was made to back down to that energy to see what was happening.
  4. On November 10, 1974, SLAC was running at 3.12 GeV. When they changed the beam energy a little bit, the count rate exploded. Particles were appearing everywhere. When they adjusted the beam energy again, they saw hundreds and hundreds more events than the regular event rate.
- **F.** At this point, the two stories converge; the particle that was being discovered at Stanford was the same particle that Ting had discovered earlier at Brookhaven. Ultimately, the particle came to be called the *J/psi*, a combination of the names given to it at both laboratories.

III. Why was the discovery of this particle so exciting?

- **A.** First of all, its narrowness was a big surprise. In this context, *narrowness* means that it has an extremely definite energy or, if we're thinking quantum mechanically, it lives for a very long time.
  1. If we think about the Stanford experiment, we note that e+/e– pairs annihilate, and a new particle is formed. We can determine its quantum numbers, including its mass, which was 3 GeV.
  2. We would expect that the J/psi would decay immediately because all the other particles in the zoo decay very rapidly, and the more massive they are, the more rapidly they decay. This particle lived for a very long time. Of course, its lifespan is still fractions of a second, but in the particle physics world, that's a long time.
  3. No one had ever seen a meson like this one, but almost immediately, physicists figured out what it was. In fact, some scientists had predicted what it was before it was even seen.
- **B.** In the years preceding this discovery, two predictions had been made.
  1. Remember the quarks that we've talked about. We have up quarks and down quarks, which are similar. They're both quite light and they make up most of the ordinary world. One of them, the up quark, has charge 2/3. The down quark has charge –1/3.
  2. We also have the strange quark, which has a charge of –1/3. It's just like a down quark, only heavier and unstable.

3. The two light quarks and one heavy quark make a sort of funny pattern. If we want to have symmetry, we ask why we don't have a heavier version of the up quark with a charge of 2/3.
4. Even in 1964, physicists had thought about that question as soon as the three quarks had been proposed. Sheldon Glashow and James Bjorken published a paper in 1964 suggesting that this particle existed. In fact, they thought that the existence of such a particle would be charming because it would make the picture so elegant. Thus, they called it the *charm quark*.

C. As the years went by, stronger arguments were made for the existence of a charm quark. Glashow, along with two other scientists named Iliopoulos and Maiani, made a subtle theoretical argument for what came to be known as the *GIM mechanism*.

1. Physicists had been looking for some events in bubble chambers that were not occurring, but everybody thought they should. A kaon particle, for example, can decay in many different pathways. It might turn into a pion, an electron, or something else. But one of those pathways did not occur, and it should have.
2. Glashow, Iliopoulos, and Maiani came up with an explanation that involved the use of Feynman diagrams. Remember that we have to draw every possible Feynman diagram and add them up before we know the probability for some event.
3. If we include virtual charm quarks—if we imagine creating a charm quark, then having it disappear again very quickly—mathematically, that event would cancel all the other Feynman diagrams and the final answer would be nearly 0. That would explain why there were no occurrences of a certain kaon decay in the bubble chamber.
4. This theory pins down the math of the charm quark. In order for the math to work out, a certain mass must be predicted for the charm quark. In retrospect, after the J/psi particle was found, its mass was exactly twice the predicted mass of the charm quark.

D. What is the J/psi particle, then? It's a charm/anti-charm meson. It's a new meson that is built out of the fourth quark, the charm quark, and its anti-quark.

1. In a certain sense, this object doesn't have net charm. We call it *hidden charm*. What's called *naked charm* would be if we produced a meson that was charm and anti-up or charm and anti-down. We might have naked charm in a baryon if we produced, for example, a charm up, up; or a charm down, up; or any of the quark combinations that we could imagine involving charm.
2. Thus, a new industry began in particle accelerators. Physicists began to look for all these new possibilities that could be seen in the laboratory, the new mesons and the new baryons.
3. The fact that new particles appeared just as expected from the quark model clinched the idea of quarks. In the November Revolution, the idea of quarks was transformed from an abstract and slightly radical proposition to a mainstream, well-established philosophy. The discovery of the J/psi was the critical event in confirming the physical reality of quarks.

Essential Reading:

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapters 1, 6.1–6.4.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 15.

Recommended Reading:

Riordan, *The Hunting of the Quark*, chapters 11, 13, and especially 12.

Lederman, *The God Particle*, chapter 7, from the section on "The November Revolution" up to "The third generation."

Questions to Consider:

1. In the quark model, how would you describe the J/psi particle? Is it a meson or baryon? A fermion or boson? A hadron or lepton?
2. Why do you suppose Sam Ting waited so long to publish his discovery of the J/psi?
3. These days, we might sometimes feel that small scientific discoveries receive a lot of "hype." Could the November Revolution have been one of the first public relations hypes of physicists—an attempt to excite the public and ensure continued funding? What arguments can you make against such a suggestion (or for it?)

Lecture Sixteen

A New Generation

Scope: The last of the great surprises in particle physics was a new layer of particles with the discovery of the tau lepton. As we know, once we find one new particle, symmetry arguments compel us to look for others, which we found—the tau neutrino and the bottom and top quarks. What do we learn when particles are predicted before they are discovered? We conclude by revisiting the periodic table of particle physics, including all the new particles.

> Inventions have long since reached their limit, and I see no hope for further development.
>
> —Julius Sextus Frontinus (highly regarded engineer in Rome, first century A.D.)

> *Pastore*: Is there anything connected in the hopes of this accelerator that in any way involves the security of the country?
>
> *Wilson*: No, sir; I do not believe so.
>
> …
>
> *Pastore*: Is there anything here that projects us in a position of being competitive with the Russians, with regard to this race?
>
> *Wilson*: Only from a long-range point of view, of a developing technology. Otherwise, it has to do with: Are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about. In that sense, this new knowledge has all to do with honor and country but it has nothing to do directly with defending our country, except to make it worth defending.
>
> —Excerpt from testimony before the Congressional Joint Committee on Atomic Energy, April 16, 1969

Outline

I. Some older physicists might look back on the 1970s as a golden age of particle physics. The discovery of the J/psi during the November Revolution was the highlight, but many other discoveries were also made, some of which we will discuss in this lecture.

- **A.** The quark model had at first been tentative but was later fleshed out. This was followed by the theory of QCD, which transformed the idea of quarks into a mathematical framework that could be used to make quantitative predictions about quarks.
- **B.** The significance of the J/psi particle was that its behavior and properties made sense in relation to the theory of QCD.
  1. Think, for example, about the most distinctive characteristic of the J/psi particle: It is "narrow," which means it lives for a long time. Why? It is a charm and an anti-charm. Why don't the two particles annihilate, like matter and antimatter? The answer comes from the mathematics of QCD.
  2. QCD says that when two quarks are far apart, they attract each other very strongly, but if they're close together, they don't feel a strong attraction. The closer they get, the freer they become. Further, in quantum mechanics, the more massive the quarks in the meson are, the smaller the effective distance between them becomes.
  3. The charm and anti-charm quark are, in a real sense, very close to each other in the J/psi particle. Because they are so close, they are almost completely free particles.
- **C.** After the discovery of the J/psi, the theory of QCD began to spread rapidly and become well established in the physics community.

II. Experimentalists began working to prove or disprove the theory of QCD, which led to some "big surprises" in the field. Ultimately, these surprises fit beautifully with the theory of quarks and QCD.

- **A.** A couple of years after the discovery of the J/psi, a physicist named Marty Perl at Stanford discovered a new lepton.
  1. Obviously, we knew about the electron and the muon, which was a heavy version of the electron. Perl had now found a third lepton. It had electric charge, just like the electron. It had spin 1/2. It did not

interact strongly. It was truly a lepton, just like the electron and the muon. It was like a third generation of these other lighter leptons. Perl called this particle the *tau lepton*, or *tau particle*.

2. What does the discovery of this particle tell us? Imagine trying to organize the fundamental particles into a kind of periodic table.
   a. Because the quarks and leptons are so different, we'll keep them separate. The lightest quarks, the up and the down quarks, are in a row by themselves. They're distinct from each other. They have different charges. Next, we have the two lightest leptons: the electron and the electron-flavored neutrino. Those four particles compose the world we live in.
   b. Next, we've got a kind of photocopy, or second generation. The strange quark is a heavy version of the down quark. It has the same charge and the same spin, but it's heavier and radioactive. In 1974, we also discovered a heavy version of the up quark, which is the charm quark. Our table now has up and down quarks and charm and strange quarks.
   c. What is analogous in the lepton sector? There, we have the muon and the muon-flavored neutrino. We have a complete second generation of quarks and leptons.
3. This second generation of particles is still kind of mysterious. They come raining down on us in cosmic rays—strange quarks, muons, and muon neutrinos but not so many charm quarks. They also exist fleetingly as virtual particles. They may exist in certain unusual astronomical phenomena, such as massive neutron stars.
4. Perl now discovered one more lepton. Imagine that beneath the electron and the muon in our table is a new particle, the tau particle. This discovery led us to expect the discovery of a row of new particles corresponding to the tau neutrino. Further, if we have a new generation of leptons, we should be able to find a new generation of quarks, heavier still and even more radioactive.

B. The discovery of the third generation of quarks came quickly by Leon Lederman and a team at Fermilab.
1. Fermilab is a giant ring, similar to the Brookhaven facility, but it is no longer a cyclotron. It is made up of a number of magnets that guide protons around in a circle. There are also electric fields so the protons gain more and more energy as they go around the ring.
2. In 1977, this facility could produce protons with an energy of 200 GeV. Aiming that amount of energy into a target should enable production of a new particle of nature.
3. Think about our periodic table. We have an up and a down quark in the lightest generation, and the down quark, in a certain sense, is a little bit lighter than the up quark. In the next generation, the strange quark is quite a bit lighter than the charm quark. If the pattern continues, the new quarks should match the known ones in charm and spin, but be heavier still.
4. These new heavy quarks in our chart are now called top and bottom, or occasionally, truth and beauty. Lederman found the lighter of these, in the form of a bottom and an anti-bottom quark bound together in a meson, now called the upsilon. This is analogous to the discovery of the J/psi, also a meson (a charm and an anti-charm quark bound together).

C. These new bottom quarks are so massive that the theory of QCD could start to make some quantitative predictions about the lifetime and the decay products and the quantum numbers—almost everything that could be measured—about this bottom/anti-bottom meson.

D. Thus, we had discovered a third generation of electron-like particles, or lepton, the tau. We had also discovered a third generation of quark. What would be the next? We should find a tau-flavored neutrino, which would be difficult to detect but was found a couple of years ago. There should also be a final quark that comes under the up quark and the charm quark, with charge 2/3; this would be the top quark.
1. The top quark was expected to be heavier than the bottom quark, but nobody knew exactly what its mass should be.
2. Remember that the theory of QCD is a renormalizable quantum field theory, meaning that in making calculations from it, some infinities arise mathematically, and some properties, including the mass of fundamental particles, cannot be computed.
3. QCD can't predict the mass of a top quark, but we can make some educated guesses about it by looking at data.
   a. Physicists already had an idea for the mass of the charm quark by considering events in which a charm quark might appear virtually, very briefly, then disappear again.

b. We can create a charm quark out of nothing if we give it back again, even if we don't have enough energy to actually make it come free. The act of pulling the charm quark, or any quark, out of the vacuum affects observables.
c. If we calculate with Feynman diagrams, we must include every possible splitting of the vacuum into particle/anti-particle, which will change the probability a little bit. This kind of calculation is called *precision particle physics*.
d. If we make a highly precise measurement, then make a careful calculation, we can compare the measurement with the calculation, and we may be able to deduce the mass of this one last unknown quark, the top quark.

E. The top quark was finally found in 1995 at Fermilab, which is now called the Tevatron, because its energy has been upgraded from billions of eV to trillions. That's the energy required to produce these ultra-massive top quarks and anti-top quarks.

III. Let me tell you a little bit about the sociology of modern particle physics and these gigantic physics facilities.

A. The accelerators at Fermilab and SLAC are gigantic. The area where the collisions take place has detectors the size of buildings and teams of as many as 500 physicists working on these experiments.

B. At Fermilab, two very narrow beams counter-rotate in the accelerator. The protons go one way; the anti-protons go the other way. The goal is to make the protons and anti-protons run into each other.

1. These particles have a probability of interacting, but the probability is not 100 percent. Some of them will interact, and some of them will pass on by and continue to circle.
2. The rings of the accelerator are designed to be slightly off kilter so that most of the time, the protons and anti-protons pass by each other. In a couple of spots, the rings cross paths; those are the interaction regions where the detectors are set up.
3. At the time of the search for the top quark, two teams were working at Fermilab completely independently. Both teams ultimately came up with data, and their two publications agreed, within experimental uncertainties, on the mass of the top quark.

C. We are now in a period of consolidation.

1. The tau neutrino was really the last discovery to be made, and it clarified and consolidated the standard model of quarks and leptons. We now believe that we have a complete list of particles, with no evidence that there is a fourth generation.
2. In fact, we have now seen hints that a fourth generation does not exist. A fourth-generation neutrino could be very light and, if it existed, we would already have found evidence of it.

D. We now seem to have a well-established framework for understanding the world, including six fundamental quarks, up and down, charmed and strange, top and bottom, and six fundamental leptons, electron and electron neutrino, muon and its neutrino, tau and its neutrino.

E. However some people are wondering how many fundamental particles we can account for before we start to ask if the story goes even deeper. Someday, we might be able to go beyond the current standard model.

Essential Reading:

Schwarz, *A Tour of the Subatomic Zoo*, chapter 7.

Kane, *The Particle Garden*, chapter 5, to p. 8.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 7.

Recommended Reading:

Riordan, *The Hunting of the Quark*, chapter 14.

Lederman, *The God Particle*, chapter 7, section called "The third generation"; chapter 8, section called "Search for the top."

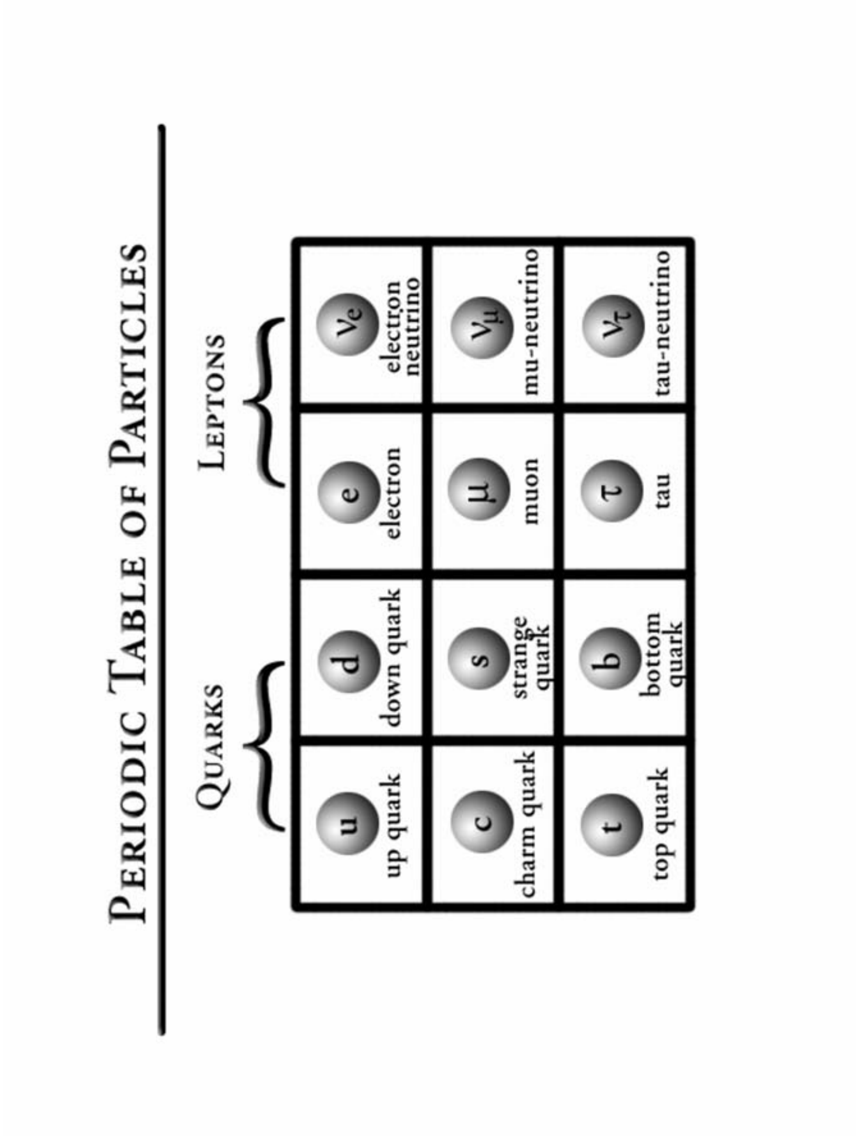
Questions to Consider:

1. Is it possible that we might someday find a totally new *fourth* generation of particles? What arguments can you make for and against this possibility?

2a. Why did it take so long to find the top quark and the tau neutrino? Both were discovered at Fermilab within the last several years. Do you think that the difficulties associated with discovering these particles were fairly similar or totally different?

2b. The top quark mass is about 170 GeV, compared to a proton mass of about 1 GeV. What element in the periodic table has a mass that large? (Bear in mind, the top quark is still considered a fundamental, elementary, pointlike object.) How many constituents does the "mass equivalent" element you found have?

Periodic Table of Particles



Lecture Seventeen

Weak Forces and the Standard Model

Scope: Progress in the 1960s and 1970s was not limited to understanding strong forces and quarks. We were also homing in on the weak force, the source of beta decays and the only force felt by the ghostlike neutrinos. It was a struggle at first. Scientists desperately wanted a field theory (like QED or QCD) for the weak force, but they couldn't make it work until the introduction of a novel particle called the *Higgs*. In this lecture, we cover the theory of Weinberg, Salam, and Glashow: the electroweak theory that unified the fundamental weak, electric, and magnetic forces. This has been one of the central goals of particle physics for a long time: to "unify" disparate laws into one single, simple, coherent whole. Just how unified are the forces now? At this point, we can summarize everything we know about particle physics: the players, the forces, and the rules! This is what we mean by the *standard model*. Do we now have the fundamental tools for understanding all microscopic phenomena?

> I will not try to define beauty, any more than I would try to define love or fear. You do not define these things; you know them when you feel them.
>
> —Steven Weinberg (*Dreams of a Final Theory*, p. 134)

Outline

I. At this point in the course, we have almost all the ingredients—the history, concepts, and terminology—to talk about the standard model of particle physics, which we believe explains the fundamental constituents of our world. One important ingredient that we are still missing is the weak force.

- **A.** The theory of the weak force that we've talked about so far is an old one, dating back to the 1930s. Enrico Fermi had tried to explain beta decays, in which a nucleus spontaneously transforms itself into a different kind of nucleus and loses an electron and a neutrino.
- **B.** Fermi's theory was not a particularly deep one. Although it served to make useful calculations, it began to break down if people tried to push it to make highly accurate predictions. Feynman taught us the importance of accounting for vacuum fluctuations when studying the electric forces of nature. If we attempt to account for these fluctuations in Fermi's theory, the result is infinity and nonsense.
- **C.** Fermi's theory also makes a prediction about weak interactions in particle collisions. In collisions, just as in decays, particles can come together, interact weakly, and transform. However, as higher energies are achieved, the weak force becomes stronger. The strong force becomes easier to predict at higher energies, but the weak force is exactly the opposite.
- **D.** In the late 1960s, it became clear that a better theory of the weak interaction was needed to go along with QED and QCD. Many important physicists were involved in the development of this theory, including Steven Weinberg, Abdus Salam, Sheldon Glashow, Gerard 't Hooft, and others.

II. The goal was to construct a relativistic quantum field theory for the weak force, and one of the most important ingredients for this theory would be the concept of gauge symmetry.

- **A.** Gauge symmetry relates to the fact that in working with electricity, the measure of voltage we call 0 is arbitrary. No matter what point we choose to call 0, once we've made that choice, the equations, the experimental results, and the laws of physics are the same.
- **B.** Also remember the idea of the force carrier in electricity. The classical idea is that a charged particle, such as an electron, has an electric field that reaches out into space. Imagine jiggling an electric charge, causing (electromagnetic) waves to propagate outward, similar to what you see in a pond. In quantum mechanics, we think of that propagating wave as a particle of electromagnetic energy, a photon.
  1. QED, particularly gauge symmetry, tells us everything about the photon, that it's massless, has no electric charge, and so on.
  2. QCD works in the same way. If we jiggle a quark that has color, it will propagate a gluon, and gauge symmetry tells us that the gluon is massless.
  3. The single most important character in the story of electricity and magnetism was James Clerk Maxwell, a Scottish physicist in the 1800s. Maxwell took the idea of a classical field and formulated a

mathematical field theory for electricity and magnetism, the precursor to QED. He recognized that electricity and magnetism are two facets of one universal underlying force of nature, which we now call the *electromagnetic force*.

C. As we said, in the late 1960s, physicists were trying to find an analog of this for the weak force, which is responsible for many radioactive decays, and neutrino physics. Every mathematician and physicist who tried working on this theory came to the conclusion that if gauge symmetry was a true principle of nature and they attempted to impose it on the weak force, then the weak force should have a carrier that is massless.

1. The carrier of the weak force, the particle that causes the weak force to travel from one place to another, is the *W particle*, or now, the *W* and *Z particles*.
2. The W particle is massive; it weighs almost 100 times as much as a proton. The mass of the W makes the likelihood of weak interactions improbable, because to have a weak interaction, we must, in a sense, excite the weak field. A W particle is an excitation of the weak field, a traveling wave of weakness. Thus, the weak interaction has its characteristics because its force carrier is so massive.
3. This leads to a dilemma. Gauge symmetry has helped us to understand electricity and magnetism. If we try to apply it to the weak force, however, we get results that are in direct contradiction with the data. Gauge symmetry says that the W boson should be massless, but nature says that the W boson is massive.

D. Even as QED and QCD became successful, it was difficult to make all the ideas fit together. A physicist named Peter Higgs came up with the idea that made it all work.

1. Higgs proposed that there might be a new particle of nature that nobody had thought of before. Those who were trying to understand the weak interaction adopted Higgs's idea.
2. The theory started with a what-if game. What if this new particle is everywhere? It could be a field that was present in the early universe and has spread everywhere.
3. Imagine a particle that is similar to a photon. It is a massless weak-force carrier, and it's propagating along through space that's filled with Higgs particles. The weak-force carrier bumps into Higgs particles all the time, which makes it effectively slow down. It seems to have mass because it is trying to move through this swamp of Higgs particles.
4. This idea could explain how a particle that, for other reasons, should be massless appears to be massive. In 1967, Weinberg produced a paper in which he put together a coherent mathematical framework for the weak force that took into account gauge symmetry and the Higgs particle.

E. The theory matched the data at low and high energies. As Maxwell unified electricity and magnetism, Weinberg, Salam, Glashow, and others now unified the weak force and electromagnetic forces. The weak force, which seemed so different in every respect, is really just like electricity and magnetism, viewed from a different perspective.

III. When Weinberg, Salam, and Glashow were looking at this theory, they noted that gauge invariance not only predicts the existence of the W particle, which is electrically charged and becomes massive in the presence of the Higgs field, but also the existence of another force carrier, the *Z particle*.

A. The Z particle is a consequence of the mathematics of the new theory. It is a new force carrier, which means that a new force exists. Although the masses of the W and Z particles could be predicted, the accelerators of 1967 were not capable of producing these particles.

B. The worldview at the time was as follows: We have gravity, electromagnetism, the strong nuclear force, and the weak force—four fundamental forces of nature. Then, electricity, magnetism, and the weak force were simplified; all of them were really one. However, we also seemed to have something brand new, because the weak force can be manifested in a way that is different from what we have seen before.

1. The Z boson is electrically neutral; it's a non-transformative weak force. Electrons can bounce off each other electrically, and now we have a way that particles can bounce off each other weakly.
2. Such an interaction could have all sorts of experimental signatures. For example, physicists could look for neutrinos bouncing off particles.
3. Such an event was seen at CERN, the European Center for Nuclear Research, in 1973. Using neutrino beams, researchers saw *weak neutral currents*. The term *weak* was used because the events involved the weak force, and the term *neutral* was used because the Z-zero particle was being transferred virtually between the neutrino and the target. This was the new force of nature.

C. The next hurdle was the discovery of the W and Z particles, which was made in 1983 at CERN with an Italian physicist, Carlo Rubbia, as the lead in the project.

D. The name for this theory of Weinberg, Salam, and Glashow is the *electroweak theory*; it is a mathematical field theory that is the analog to QCD. It unifies electricity and the weak force so that QED becomes part of the electroweak theory.

IV. We can now take stock of what we have been talking about throughout the course. We have in our hands all the ingredients of the standard model, even though a better title might be the standard *theory* of particle physics. Let's quickly reiterate these ingredients.

A. We have the fundamental particles of nature, which appear to be point-like, to the best of our knowledge even today. They come in two classes: quarks and leptons.

1. The six quarks are all strongly interacting. They are colored objects that get progressively heavier. We start with up and down quarks; then, heavier are the strange and charm quarks; then we have a third generation, heavier still, top and bottom.

2. In the category of leptons, we have the electron and its neutrino, a muon and the muon-neutrino, the tau and the tau-neutrino. Again, these get heavier and less stable, that is, more radioactive, as we go down in our table.

B. The forces are the electroweak force, which is described by the electroweak theory, and the strong force, which is described by QCD. Those theories are consistent with everything we've ever learned in the last 400 years about science.

1. These theories include the principle of the field and all the logical consequences of having a field that also exists in a quantum mechanical world.

2. These theories predict new particles of nature, which we call force carriers. They predict the photon, the W+/W–, and the Z particle. These theories also predict the gluons, carriers of the strong force.

C. From these ingredients of the standard model, we can calculate the observable consequences of any imaginable subatomic physics experiment. In principle and in practice, we can calculate the properties and structure of fairly complicated particles.

D. The development of the standard model stands out as a grand human intellectual achievement, although certain interesting questions remain.

Essential Reading:

Schwarz, *A Tour of the Subatomic Zoo*, chapter 6.

Weinberg, *Dreams of a Final Theory*, Chapter V, pp. 116–end of chapter.

Recommended Reading:

Taubes, *Nobel Dreams.* (Take your time and read the whole book. It's interesting and quite different from the usual, somewhat "drier," readings.)

Riordan, *The Hunting of the Quark*, chapter 9.

Lederman, *The God Particle*, chapter 7, section on "The weak force revisited"; and chapter 8, up through the section titled "What are we talking about?"

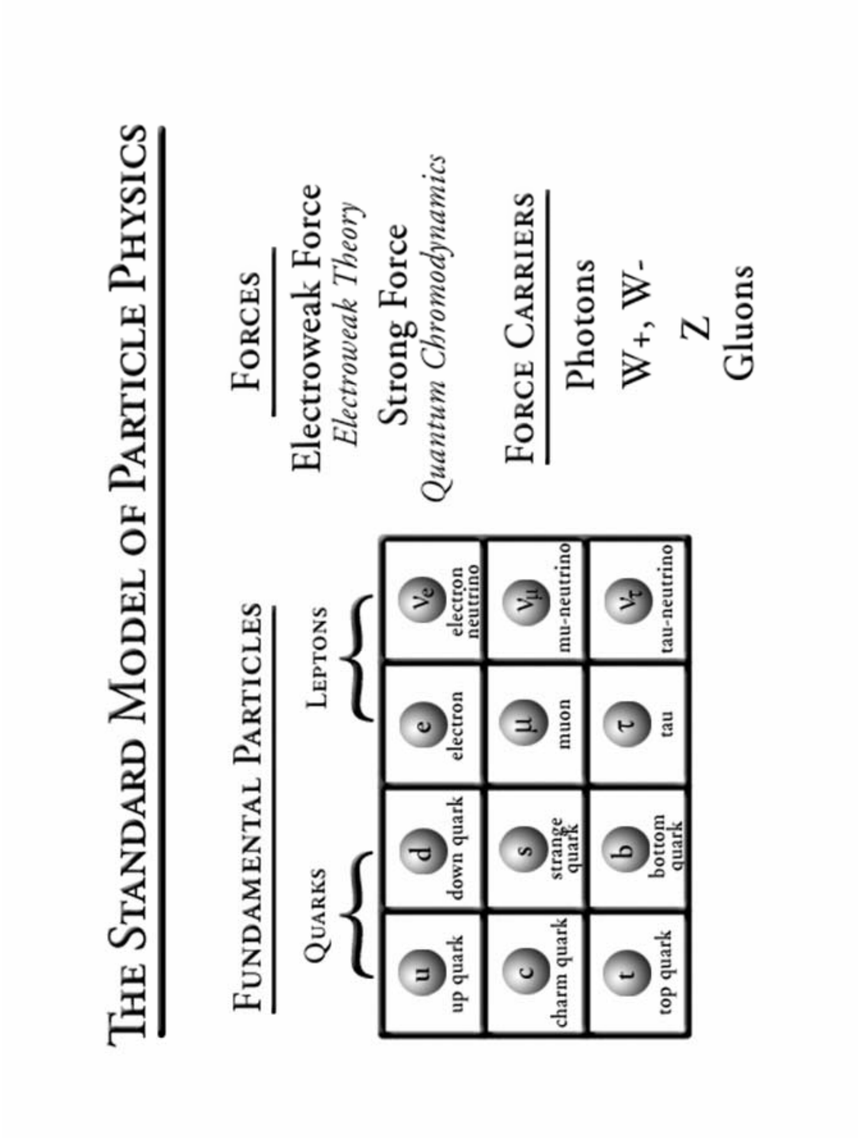
Questions to Consider:

1. What is the difference between a "charged current" weak interaction, and a "neutral" weak interaction? Can you think of a specific example for each?

2. The mass of the W and Z particles is roughly (slightly under) 100 GeV. What can you say about the *range* of the weak interaction? (Either qualitatively or quantitatively, if you are so inclined)

3. Why do physicists make such a big deal about renormalizability? What does that mean again, and why does it matter?

Diagram of the Standard Model of Particle Physics



Lecture Eighteen

The Greatest Success Story in Physics

Scope: Make no mistake, the standard model of particle physics is an impressive accomplishment, an unprecedented artwork of mathematics and physics. It is a "minimalist" theory, composed in the 1960s with the simplest available framework, and guided only by the basic requirements of quantum mechanics, relativity, and the known data at the time on the fundamental particles. It is not fully unified, but it comes close, and it is an effectively complete description of subatomic particles and forces. The standard model has been the target of more than thirty years of intense efforts to find hidden cracks or problems in it—to no avail! The unparalleled success of the standard model includes qualitative and quantitative measurements, with years of increasingly precise tests. Still, many people are left with more than a slight discomfort with this theory. Could this really be the final story? Despite the descriptive successes, we are still missing a lot of explanations.

> The most incomprehensible thing about the universe is that it is comprehensible.
> —Albert Einstein

Outline

I. In the last lecture, we talked about the electroweak theory, which ties together electricity, magnetism, light, and the weak force of nature and all the associated particles and force carriers to form a coherent mathematical framework. This lecture consolidates everything we have learned thus far.

- **A.** Let's begin with a review of the standard model. We have a set of six quarks and a set of six leptons. Each one of these is considered to be a fundamental particle of nature. It has certain properties, including an electric charge, a weak charge, a mass, a spin, and not much else.
- **B.** Those are the fundamental building blocks of all the complexity in the world, everything from the hardness of a table to the softness of human skin; the colors that we see, the light that strikes our eyes, the sounds that we make—all these can be understood as coming from the rules and the players of the standard model.
- **C.** The rules are the theories, QCD and the electroweak theory, or the Weinberg-Salam model as it's also called. The electroweak theory is a renormalizable relativistic quantum gauge field theory.
  - **1.** *Renormalizable* is a mathematical statement that says that if we include all the subtle quantum mechanics, the result is some infinities, in principle. If we add progressively smaller and smaller corrections, they add up to be infinitely large. However, if we measure a few things that the standard model cannot predict, everything else is completely finite and mathematically consistent.
  - **2.** *Relativistic* means that the theory must satisfy what Einstein has told us about the nature of space and time, including the symmetries that Einstein recognized.
  - **3.** *Quantum* means that the theory must satisfy all the laws of quantum mechanics that were first postulated in the early 1900s, then rigorously tested and proven by Heisenberg, Schrödinger, Pauli, Fermi, and many others.
  - **4.** *Gauge* refers to an abstract symmetry of nature that apparently all the fundamental forces have. Symmetry is observed when a change is made in an experiment or a theory, but all the answers come out the same. It is an invariance in a theory when viewed from different perspectives. Gauge symmetry was long observed to be true for electricity and magnetism, then later found to be true for the weak and strong forces.
  - **5.** *Field* refers to our mental image of how action at a distance takes place. How can a particle in one place "communicate" with a particle in a different place? We visualize space as being filled with fields. Everything in these quantum field theories is a field.
- **D.** The theory entails some fancy mathematics, but in the end, the story is one that we can think about in fairly concrete terms and has been successful aesthetically, mathematically, and physically.

II. First, let's examine the aesthetics.

- **A.** This theory has built into it essentially every symmetry of nature that we have been able to think of and that we might hope exists in the universe.

B. It is also a minimal theory. It is extraordinarily simple in the sense of having a few ingredients and a few ideas behind it. We have observed, for example, the six quarks and six leptons in the laboratory, and we don't include anything else in the theory except the Higgs particle.

   1. This theory was essentially complete in 1967, and it hasn't been tweaked in any significant way since then.

   2. In biology, chemistry, geology, and other sciences, we often start with a simple approximation and make it richer as we gather more data and become more precise. In particle physics, the situation is different. We started off with the simplest theory and found that it just kept working. We built new accelerators, discovered new particles, learned a great deal since 1967, but it all fits in with the minimal electroweak theory.

C. The theory also unifies forces of nature. What we thought were completely different forces—electricity, magnetism, light, the weak force—all are just one force viewed from different angles in this mathematical theory.

D. Some symmetries of nature are broken in the standard model, resulting in mysteries, in some cases, and deeper understanding, in others.

   1. For example, left and right are no longer an exact symmetry of nature itself. The laws of physics are different for something spinning like a left hand spins and something spinning like a right hand spins, but they're only different when you consider weak interactions.

   2. The laws are the same for electrical forces, strong forces, and gravitational forces. Only the weak force appears to violate this symmetry of nature. That's in the standard model, but it can't be explained; it is just an observed fact of nature.

   3. Other broken symmetries can be explained. For example, symmetry is broken between two of the force carriers, the photon and the Z. In some ways, they seem similar. They both have spin 1, and they carry some aspect of the electroweak force, but the photon is massless, and the Z particle is massive. That's an electroweak symmetry breaking. We believe that this breakage arises from the presence of the Higgs particle.

   4. The standard model, then, gives us an explanation for why these two forces, which we would think are completely symmetrical, seem, in fact, to be so different from each other in the real world.

III. Let's look at the mathematical success of this theory.

A. The mathematics really boils down to the fact that this theory doesn't contradict itself in any obvious way. If we calculate something, we always get finite answers.

B. There are no probabilities that can be computed in the standard model that come out greater than 1 or less than 0. Any other results would constitute a mathematical inconsistency. Earlier models had that problem, but the standard model does not.

IV. Finally, let's turn to the physical success of this theory. A theory is only good if the results it predicts match the results from the laboratory.

A. Every year, the particle data group at Berkeley puts out a collection of all the information that has been gathered in particle physics.

   1. First, it shows a summary of the standard model, including the ingredients and the formulas. Then comes a list of particles and their properties. Every piece of data in this list includes a reference to a paper or a journal article, backed up by experiments that resulted in the numbers.

   2. In fact, this tabulation can be found published in a volume that runs to hundreds of pages. What's stunning about this mountain of information is that it all comes from the first couple of pages—the standard model and the formulas for doing these calculations.

   3. To date, I know of no significant discrepancies between the theoretical calculations and the experimental observables.

B. Let's look at another success of the standard model that's a bit more qualitative but equally convincing.

   1. In 1967, Weinberg worked out a theory that predicted the existence of a new particle, the Z boson. Almost twenty years later, when we finally achieved the necessary energy to produce the Z particle, we detected its presence in a bubble chamber.

2. The marvel is that a human being made a prediction about a fundamental particle that would not be observed for twenty years. That kind of prediction of a new fundamental particle is a powerful indicator that our theory does, indeed, help us understand the world.
3. Of course, the W, the tau-flavored neutrino, and the top quark were all similarly predicted before their discoveries. In fact, the physics of the neutrino may be one of the few areas of the standard model that needs to be tweaked a bit for full understanding.

V. We should also note that even if we discover something odd about, for example, quarks, we're not going to throw out the standard model, because the model does have a bit of leeway in it.

A. Imagine that we make a discovery of a fourth generation of quarks; such a discovery would modify the standard model, but it wouldn't shatter it. The framework would still exist and could be generalized to incorporate some new heavier particles.

B. We might extend and deepen the standard model, as we have Isaac Newton's theory of gravity, but the basic model would still be accurate. No matter what we discover in the future, we're still going to have atoms and quarks, and they will continue to combine in certain ways.

C. Consider also that the standard model makes both qualitative and quantitative predictions about the existence of new particles. We can predict, for example, exact numbers for the magnetic strength of an electron. As I mentioned earlier, this number is 2.00231930435.

D. Thus, the electroweak theory may not be the ultimate theory of nature, but we know that it is extraordinarily accurate. If some new laws of physics take over beyond the standard model, we know that those laws will not affect an observable until the thirteenth digit, because we've already checked the accuracy of the first twelve.

VI. In the future, you may read articles or hear news stories about discoveries that are touted as disproving the standard model.

A. What these discoveries most likely will do is extend the standard model in an unexpected direction. We might be heading toward a deeper theory of nature, but the idea that the standard model would break down is almost inconceivable at this point.

B. That is not to say that the standard model doesn't have some bothersome aspects.
1. For example, there are twenty-three properties that cannot be computed from the standard model; they must be measured in the laboratory.
2. We also have a large number of particles, including quarks, leptons, force carriers, and the Higgs.

C. For the rest of this course, we will talk about the limitations and puzzles in the standard model, along with some even wilder speculations.

Essential Reading:

Kane, *The Particle Garden*, chapter 6.

't Hooft, *In Search of the Ultimate Building Blocks*, chapters 16 and 18.

Recommended Reading:

See recommended readings for Lecture Seventeen.

The central repository summarizing all standard model information is compiled by the Particle Data Group of Berkeley at http://pdg.lbl.gov/.

Information about the status of the standard model is usually quite technical. For example, Jens Erler and Paul Langacker at the University of Pennsylvania keep an up-to-date summary at http://dept.physics.upenn.edu/~erler/electroweak/index.html. Some of it may be readable, but for the most part, it is designed for particle physicists.

Questions to Consider:

1. What other scientific theories can you think of that are as successful as the standard model? Are they "complete"? How well do they stack up when compared with the standard model?
2. Why do I say that the standard model can't be the "final story"? In what senses is it flawed or incomplete? (Your answer may depend on your personal philosophy about science!)

Lecture Nineteen

The Higgs Particle

Scope: The mysterious Higgs particle is the least understood piece of our story so far and the *one* central part not yet directly verified. In this lecture, we ask a number of questions about the Higgs: Why should we believe in its existence? How can we picture it, and what role does it play in the standard model? Why is it so important to "find" a Higgs? How would we go about looking for such a thing, and what would happen if we looked for it and it wasn't there? We conclude by discussing the rise and fall of the superconducting supercollider (SSC), the machine specifically designed to answer our questions about the Higgs.

> No one can say whether any one accelerator will let us make the last step to a final theory. I do know that these machines are necessary successors to a historical progression of great scientific instruments… Whether or not the final laws of nature are discovered in our lifetime, it is a great thing for us to carry on the tradition of holding nature up to examination, of asking again and again why it is the way it is.
>
> —Steven Weinberg (*Dreams of a Final Theory*, p. 275)

Outline

I. We have talked about all the fundamental particles that we currently know about, except for one—the Higgs boson.

- **A.** In the standard model, the Higgs is responsible for the defining characteristic of any particle, its mass. It also functions in distinguishing between the weak and electromagnetic forces, and it may have played a role in the evolution of the universe.
- **B.** The Higgs is the most poorly understood part of the standard model to date. Everything else we have talked about has been extremely well established for many years in the laboratory. The Higgs, however, has been established mathematically but not physically. We have no direct evidence of the existence of a Higgs particle.
- **C.** Let's recall for a moment why the Higgs was proposed.
  - **1.** In trying to understand the weak force of nature, physicists believed this force should have gauge symmetry, because the other forces in the universe had gauge symmetry.
  - **2.** If gauge symmetry is observed in the weak force, as it is in electricity and magnetism, these forces will be completely symmetrical in many ways. Specifically, the weak force carrier will be massless. That idea, however, contradicted the data.
  - **3.** Every piece of data says that the weak force has very short range. It is almost a contact force, which is why it's so weak. The force carriers—the W and Z particles—are massive. How could we reconcile gauge symmetry, which says that these carrier should be massless, with the fact that they are massive?
  - **4.** The answer was a mathematical trick, the prediction or assumption of the existence of a new particle of nature.
    - **a.** Remember, in quantum mechanics, particles and waves are two aspects of the same thing. Similarly, if we think about physics as a quantum field theory, particles and fields are two aspects of the same thing.
    - **b.** This idea is most obvious in thinking about force carriers. How do I visualize a photon? First, I visualize an electric field, but that's not the photon. The photon is the traveling wave that results when the electric field is jiggled. The photon is also the particle of light.
    - **c.** Every particle of nature can be thought of in this same abstract way as the ripple in a field.
    - **d.** Thus, Higgs proposed a new field—not an electric field or a magnetic field, but the Higgs field, which permeates space. The ripple in that field would be called the Higgs particle.
- **D.** The unusual thing about this Higgs field is that it is finite but everywhere. The Higgs field exists inside of atoms in the empty space between the electrons and quarks. It even exists in outer space. It is a uniform background in which we all live.
  - **1.** Usually, we would think about outer space as being close to a vacuum. We would imagine that an electric field is strong when it's near an object but that it then fades away.

2. With the Higgs, however, to make sense of the weak interaction and to make the theory mathematically consistent, we were obligated to postulate that the Higgs field is everywhere.
3. When I walk through the room, then, I'm walking through a sea of the Higgs field. What would be the effect on me? That depends on the interaction of the particles in my body with the Higgs field.
4. One of the things that would happen as I'm walking, if the particles in my body are interacting with the Higgs field, would be some sort of resistance to my motion.

E. Before we talk about the search for direct evidence of the Higgs, which we have not yet found, I want to touch on one other aspect of it.

1. In nature, the weak force and the electric force seem completely different. One of them has to do with radioactivity; the other is everyday life. The carrier of electricity is massless, which means that generating electricity and electric forces is easy. But the carrier of the weak force is massive, which means that the likelihood of weak interactions is improbable.
2. A symmetry in the standard model says that these two forces of nature are the same. How, then, does that symmetry get broken? How does the universe change from one in which weak forces and electric forces are identical to the one we live in where the forces are so different?
3. The answer is that the Higgs is responsible for symmetry breaking. In the standard model, the W and Z bosons interact with the Higgs field very strongly and it slows them down a great deal. They become massive.
4. We call this phenomenon *electroweak symmetry breaking*. If we want to understand why the weak force and the electric force seem to be the same yet are so different, we must postulate something like the Higgs.

II. How do we look for a particle like the Higgs? With the neutrinos, a mathematical theory predicted their existence and the exact probability of their interaction. The situation is a little different with the Higgs.

A. The standard model cannot tell us how massive the Higgs field is. The phrase *how massive* refers to how much energy we have to pour into a small region of space to create a ripple in the Higgs field.

B. Again, imagine that we live in a sort of unusual fluid, and we want to create a wave. In water, the slightest perturbation will create a wave, but that is not true of the Higgs field. The Higgs is so massive that we need to add a lot of energy to create a ripple, which would be a particle and would leave direct evidence behind in a bubble chamber.

C. We could find this particle through a direct or an indirect search.

1. The indirect search would be to look for the presence of a Higgs, because any particle of nature, if it's real, can be virtually created for a very short time, then would disappear again. This is how we began to search for the top quark before we had accelerators that were energetic enough to actually make one in the laboratory.
2. This method is called *precision physics*. We make very accurate measurements and very accurate standard-model calculations. We have only one unknown—the mass of the Higgs—therefore, we can compare the measurements and the calculations and try to deduce the mass of the Higgs.
3. Physicists have been trying this method for thirty years now and are beginning to hone in on the mass. Unfortunately, the Higgs effects on other processes tend to be extremely subtle compared to even the small effects of a top quark. The best guess for the mass of the Higgs today from precision data is somewhere between 100 times proton mass and 200 times proton mass.
4. If we know this range, why don't we make a Higgs particle? At Fermilab, we can achieve a trillion eV. In principle, that's more than enough energy to create a Higgs. What happens, though, when we add all this energy to a small region of space? We would produce the whole zoo of particles, but the probability of producing a Higgs is so small that we would not expect to have seen one yet, even given the millions and millions of other quantum particle production events that we have observed.
5. At Fermilab, the strategy to increase the likelihood of seeing an event has been to upgrade the intensity of the beam to increase the number of proton and anti-proton collisions. In Europe, at CERN, the strategy is to increase the energy. Around 2007, CERN will be able to achieve 14 trillion eV, which will certainly be enough energy to see a Higgs if they exist.
6. In the 1980s, the United States began a project to build a truly gigantic accelerator—a superconducting supercollider. The project was abandoned in the 1990s because of lack of funding.

III. I believe that the demise of the superconducting supercollider was symbolic of a shift in U.S. priorities regarding particle physics compared to other areas of physics and other sciences.

A. From World War II until the 1990s, particle physics was at the top of the list for funding and facilities. This field was viewed as the most fundamental and, therefore, the most worthy of all the sciences.

B. That idea seems to have changed now. Particle physics is still very much alive, but now, it is one player among all the branches of physics and, indeed, among all the branches of science.

C. Let's finish this lecture by asking, "What if we had built this superconducting supercollider and hadn't found the Higgs?"

1. Mathematics tells us that we would expect to find this particle, but we could easily imagine that the Higgs might not show up the way we would expect it to. What would happen if we took the Higgs out of the standard model?

2. The answer is that some aspects of the model would survive, but in some ways, the standard model would collapse on itself. In particular, if we try to calculate events at a couple of trillion eV, then the theory would start to yield infinities. In other words, the theory is fine at low energies, but when we reach the energies of superconducting supercolliders, the theory might break down and yield answers that don't make sense.

3. That fact would tell us that something deeper is going on. The Higgs is a minimal theory. That is to say, it is the simplest possible mechanism we have come up with that is consistent with everything we know so far and makes the theory coherent.

4. I might almost guarantee that something will happen at a trillion eV that we don't know about today. The symmetry of nature between electric and weak forces is going to merge or break down at those energies, but we're not quite sure exactly how.

5. If we find something else, we would have to reconstruct the standard model to account for the Higgs sector.

D. The Higgs, then, is the last piece of the standard model and the most important in the sense of understanding mass, the fundamental property of everything, and understanding symmetry breaking, which is the key idea that unifies the weak and electromagnetic forces. And it's the one piece that we have not yet verified in the laboratory.

Essential Reading:

Kane, *The Particle Garden*, chapters 3 and 8.

Weinberg, *Dreams of a Final Theory*, chapter XII and afterward.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 9.2.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 11.

Recommended Reading:

Lederman, *The God Particle*, chapter 8, second half, starting from "The Standard Model is a shaky platform."

http://www.hep.ucl.ac.uk/~djm/higgsa.html. In 1993, the then-current Science Minister of the United Kingdom, William Waldegrave, issued a challenge to physicists to answer the questions "What is the Higgs boson, and why do we want to find it?" on one side of a single sheet of paper. This link is David J. Miller's prize-winning "qualitative lay-person's explanation." Other replies can be found at http://hepwww.ph.qmw.ac.uk/epp/higgs.html.

Questions to Consider:

1. Leon Lederman, former director of Fermilab and Nobel Prize winner, wrote a book about the Higgs called *The God Particle*. Few people in the physics community use that name for the Higgs. Why do you suppose he chose that title? Are you sympathetic with his choice? Why or why not?

2. If you could go back in time and cast the deciding vote in the Senate to end or continue construction of the superconducting supercollider, how would you vote? Why? What factors would influence your decision most strongly?

Lecture Twenty

The Solar Neutrino Puzzle

Scope: Neutrinos are among the most mysterious and intriguing particles in the standard model. There remains a great deal that we do not know about them. We have always assumed that they are massless, but is that really the case? What would happen if they did have mass? We might also ask about solar neutrinos. Evidence suggests that far fewer neutrinos are coming from the sun than we would expect. Is there a way to make sense of that? Could the answer be something novel about the way neutrinos behave? In this lecture, we discuss physics deep in mine shafts, an alternative to accelerator physics. We also talk about neutrinos changing "flavor." What does that term mean, and how could we ever tell? We already have a small but growing body of evidence for "neutrino physics beyond the standard model." If we establish this science, why won't it "shatter" the standard model?

> You could argue that all the experiments are simply wrong, but this is highly unlikely.
> —Sudbury Neutrino Observatory Web page

Outline

I. The neutrino is an intriguing particle and still not fully understood. Just recently, some data have hinted at the possibility that the standard model may not be completely correct concerning neutrinos.

- **A.** Remember that the neutrino is a lepton. It has no mass, no charge, and no color. The only force of nature it feels is the weak force.
- **B.** The massless aspect of the neutrino is part of its mystery. If a particle is massless, it is incredibly easy to produce.
  - **1.** The other massless particle with which we're familiar is the photon. A photon is a traveling electromagnetic energy bundle, but it has no rest mass. It is always moving at the speed of light.
  - **2.** A neutrino is quite different. It is not a force carrier. It is itself one of the fundamental constituents. Yet, relativity tells us that if it is massless, it will always be moving at the speed of light.
  - **3.** We might ask: Why is it massless? The photon is massless because of gauge symmetry, but there is no such principle associated with the neutrino.
  - **4.** Suppose that we measured the mass of the neutrino and it turned out to be .00001 in some unit system, a tiny but non-zero number. Would that break the standard model? The answer is no. We would have to adjust the standard model in some places, but finding mass in a neutrino would not break the model. In fact, we now have some hints that the neutrino may have mass.
- **C.** Another important aspect of neutrinos is that they seem to exist in three flavors: the electron flavor, the muon flavor, and the tau flavor.
  - **1.** We talk about electron number as a property of particles. An electron or an electron-neutrino both have electron number 1. Apparently, electron number is a conserved quantum number.
  - **2.** As particles move and interact, an electron could just bounce, preserving electron number, or it might undergo a weak interaction. A W boson might be exchanged, and the particles would transform. The electron will transform but only into an electron-type neutrino to conserve total electron number.
  - **3.** Again, until recently, it was believed that electron number, as well as muon number and tau number, were absolute exact conserved numbers. We have not discovered any symmetry of nature that would correspond to conserving electron number; it seems to be an accidental conservation.

II. Let's leave the world of neutrinos for a moment and talk about the sun. The two subjects seem disconnected, but they are closely tied together.

- **A.** For many years, physicists and astronomers have been trying to understand what the sun is and how it works. These scientists have constructed what we might call a standard model of the sun.
  - **1.** This truly is a model, not a fundamental theory of nature. It is a collection of many branches of physics—heat, thermodynamics, light, sound, vibration, and materials—put together to describe the sun. This model is very successful and, to a certain extent, gives us a good understanding of the sun.

2. One aspect of that understanding involves the nuclear reactions at the core that power the sun. We know how many such nuclear reactions are occurring, and we know that they involve protons smashing together with other protons at very high temperature and energy to form nuclei.
3. When protons bind to protons, in order to stabilize, one of the protons must turn into a neutron; that is a weak decay that releases a neutrino. According to the laws of nuclear physics, if we know how many nuclear reactions are going on, we know exactly how many neutrinos are coming out of the sun.
4. The standard solar model makes a definite prediction about how many neutrinos flow out of the sun every second, which is 60 billion neutrinos per square centimeter per second everywhere in the orbit of earth.

B. In the 1960s, a physicist named Ray Davis thought that with a big enough detector, we should be able to see neutrinos from the sun.

1. Davis looked at nuclear reactions in which a neutrino hits a nucleus and makes a transformation occur. One such reaction was in a chlorine atom. If a chlorine atom is hit by a neutrino, the neutrino will convert into an electron because it's a weak interaction, and the chlorine nucleus will convert into an argon nucleus, which forms a radioactive gas and should be easy to detect.
2. Davis filled a railroad car with carbon tetrachloride, a cleaning fluid, then buried it in a mine. He buried the material, because otherwise, he would get too many other interactions from cosmic rays.
3. The idea was that a couple of times a day, one or two atoms in the railroad car would transform from chlorine into argon. The argon would bubble up to the top of the tanker and be collected, then the radioactivity would be detected by a Geiger counter.
4. Davis's experiment worked, but he collected only about a third of the neutrinos that the standard model predicted he would. This was the first direct evidence that neutrinos come from the sun, but the fact of the missing two-thirds of the neutrinos was bothersome.

C. Davis and others worked to solve the solar neutrino puzzle.

1. Davis placed a highly radioactive source next to his tank and collected the number of neutrinos he expected. This result points to the idea that there really is something special about the neutrinos coming from the sun.
2. In the 1980s, the United States, the Soviet Union, and the Europeans conducted similar experiments using tanks of gallium, which is liquid metal and transforms into germanium. These results showed that the number of neutrinos coming from the sun was less than predicted by a factor of two.
3. Japan entered the story with a giant water detector, a tank of very pure water, called Kamiokande, deep in a mine in Japan. This experiment found something extra.
   a. When a neutrino hits the nucleus or the electrons in the water tank, the transformation occurs. Some energy is released, and the outgoing particles carry the momentum of the neutrino. If the neutrino comes in from a certain direction, we see a spray of particles going out in that direction.
   b. Using light detectors, scientists at Kamiokande saw for the first time that the neutrinos really were coming directly from the sun. In fact, Kamiokande and its second-generation upgrade, Super Kamiokande, have produced images of the sun.
4. Despite all these efforts, we were still left with the solar neutrino puzzle: too few neutrinos arrive from the sun.

D. In working on the puzzle, scientists saw two obvious points at which our understanding might be incorrect.

1. First, the standard solar model may be wrong; the sun may produce fewer neutrinos than we thought.
2. The other problem could be with the standard model of particle physics. Suppose that an electron-flavored neutrino, which is produced in the nuclear reaction in the sun, travels the long path from the sun to the earth, and as it's moving along, imagine that it could oscillate in flavor from an electron-type neutrino to a muon-type neutrino.
3. The laws of quantum mechanics say that if neutrinos are not truly massless particles, then this can happen. In fact, we've seen exactly the same thing happen before with quarks. (A down quark can oscillate into a strange quark.)
4. How do we visualize this phenomenon? Imagine that a number of neutrinos leave the sun; they are all electron types because that's what the nuclear reactions in the sun produce. As they travel, they oscillate and, by the time they reach earth, half might be electron-flavored and half, muon-flavored. Unfortunately, our detectors have been designed to look only for electron-type neutrinos.

E. What experiment would verify that the total number of neutrinos predicted is coming out of the sun, but they are changing flavor before they reach earth?
   1. The Canadians built an underground neutrino detector called the Sudbury Neutrino Observatory (SNO). SNO is a water detector and can see transformations, the same as all the other detectors. SNO also has the possibility of measuring a weak neutral current.
   2. Remember that the weak force can manifest itself in two ways according to the standard model. First, the weak force can be seen when a neutrino changes into an electron and, at the same time, transforms whatever it is hitting from one nucleus into another. That's the usual beta decay weak interaction.
   3. The weak force can also be mediated by the exchange of Z bosons. This interaction is neutral; there is no transformation. A neutrino comes in, exchanges a virtual Z boson, and hits the nucleus, but no transformation occurs. In detecting the neutrino in this weak interaction, all that can be observed is a recoil of the nucleus.
   4. SNO is capable of detecting any flavor of neutrino and is beginning to publish results. Scientists there are seeing the full solar neutrino flux when they look in this weak neutral sector. Thus, the sun is behaving just as we thought it should.

III. We seem to now have evidence that neutrinos can change flavor and, therefore, according to quantum mechanics, neutrinos are massive. What is the significance of this discovery?
   A. The most important theoretical argument for the significance of this finding would be that it is a break in the standard model. Such a break would mean that our understanding of the world is incomplete, which is exciting. The discovery that the neutrino is not massless would also enhance the standard model by making it more symmetrical.
   B. The practical aspect of this discovery lies in an astrophysical use that no one would have dreamed of even twenty years ago. We have now formed images of the core of the sun using neutrinos that other scientists may be able to use as tools for gathering information.
   C. The third consequence of this discovery relates to cosmology, the study of the universe.
      1. If we consider that astronomically huge numbers of neutrinos exist in the galaxy and that they have mass, we must ask whether they will have a gravitational effect on the universe.
      2. As the universe is expanding, all these neutrinos are pulling it back, and they may produce enough gravity to help halt the expansion and cause the opposite of the Big Bang, the Big Crunch. The fate of the universe may rest in this exotic particle.

Essential Reading:

Kane, *The Particle Garden*, chapter 5, pp. 86–90.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, pp. 143–145.

't Hooft, *In Search of the Ultimate Building Blocks*, chapter 19.

Recommended Reading:

See John Bahcall's Web site, http://www.sns.ias.edu/~jnb/ (check the link on the left for "popular accounts").

The SNO collaboration's Web site, http://www.sno.phy.queensu.ca/, is a good place to find its latest news and summaries of other experimental efforts.

Questions to Consider:

1. Until SNO, all the solar neutrino experiments agreed that there was a *deficit* in the number of electron neutrinos from the sun. What did SNO do that was new and helped resolve whether the deficit comes from the *solar* physics (e.g., lower temperature in the sun's center than we thought) as opposed to *neutrino* physics (e.g., flavor oscillations)?
2. Most physicists have speculated that the electron neutrinos from the sun might oscillate into mu or tau neutrinos. Others have claimed that the electron neutrinos might oscillate into yet another kind of neutrino, a *sterile* type that would not interact in any way with ordinary detectors. What would be the *difference* in what SNO would see in these two scenarios?

Lecture Twenty-One

Back to the Future (1)—Experiments to Come

Scope: This lecture highlights some of the current issues and directions in experimental particle physics. Many physicists continue to look for small deviations in the standard model, but we are also looking farther afield, for physics beyond the expected. One of the big efforts today is a search for violations of matter/antimatter symmetry. Some such searches take place at "bottom factories," high-energy accelerator facilities redesigned to produce heavy quarks. Novel neutrino beams that travel vast distances through the earth are also under construction, as are new high-energy machines, including RHIC, designed to study the conditions of extreme density and temperature that existed a fraction of a second after the Big Bang. Plans are underway for next-generation accelerators. We'll close with the increasing role of non-accelerator physics, including the giant arrays of detectors built in the desert, tundra, and under the Antarctic ice sheet to look for ultra-high-energy cosmic rays.

> It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories instead of theories to suit facts.
> —Sherlock Holmes (*Scandal in Bohemia*)

Outline

I. In the last couple of lectures, we've talked about puzzles that physicists are investigating today, such as the puzzle of the Higgs boson or the mass of neutrinos. This lecture looks at some of the other directions that particle physics is taking by focusing on current programs led by experimentalists.

II. The first project we'll look at is called *CP violation*, which might be thought of as the difference between matter and antimatter.

- **A.** *CP violation* refers to a breaking of a symmetry that for years, many scientists believed should be present. This symmetry is between particles and anti-particles.
- **B.** We've talked about how the weak interaction violates the symmetry of handedness. If you have a particle that's spinning in a left-handed sense and it interacts weakly, it will have a completely different interaction than a particle that is spinning in a right-handed sense. Only the weak interaction violates parity or mirror symmetry.
- **C.** Even after the discovery of parity violation, physicists thought that matter/antimatter symmetry was an elegant symmetry of nature.
  1. Imagine that you have some heavy particle that can decay, according to quantum mechanics, in various ways. If you're working with high energy, there might be various pathways or possibilities for how the particle might fall apart.
  2. We would expect that if matter and antimatter are symmetrical, the way a particle would decay would match with the way its anti-partner would decay. Of course, the particle will decay into certain particles and the anti-particle might decay into the anti-particles, but the relative probabilities should be the same.
- **D.** In 1964, Cronin and Fitch performed an experiment in which they looked at the decay of one of the heavy mesons now called a *kaon*.
  1. The kaon is a strange particle. Microscopically, it consists of a strange quark and an anti-down quark.
  2. Remember that a strange particle has charge –1/3, and a down quark has charge –1/3. An anti-down is +1/3. This kaon, then, is a neutral particle.
  3. The kaon also has various decay possibilities. A kaon decay might result in an electron and a pion. The electron would be negative and the pion would be positive so that total electric charge is conserved. The decay must also result in some electron-type neutrino to cancel the electron number that is lost. We will see the electron and the pi+, or we might see an anti-electron and a pi –, the anti-particles.
  4. We might also expect, given that we started with a neutral object, that these two results would be equally likely: matter and antimatter are symmetrical.

E. Cronin and Fitch discovered, however, a violation of symmetry. For every 1,000 times the kaon might decay in one path, it would decay 1,003 times in the other path. A great deal of data had to be collected before this tiny break in matter/antimatter symmetry was recognized.

F. How was this break built into the standard model?

1. The answer is rather subtle and mathematical, but the general idea is as follows: The standard model includes an experimental number that must be measured, and this experiment did that measurement. You might think of this number that belongs in the standard model as telling us how much CP violation, or matter/antimatter discrepancy, there is.
2. The number can range from 0 to 1. Zero would mean no breaking, perfect symmetry. One would mean a 100 percent breaking, absolutely no symmetry. In principle, the number could have been anything, but in practice, it's .003.

G. Physicists were amazed by this breaking of symmetry and the expansion it offered in our understanding of antimatter.

1. We might use this knowledge to ask very basic questions, such as why the world is made of matter. Why isn't it made of antimatter or, at least, why isn't it half antimatter?
2. If matter and antimatter are completely mirror images, then every time an event created a particle, it would be equally likely to create an anti-particle. Go back all the way to the Big Bang when all matter was originally produced from a hot bundle of energy. We should have equal numbers of electrons and anti-electrons, protons and anti-protons, and so on.
3. Most of these would have been annihilated, and the universe today would basically just be energy. Yet the universe that we live in appears to have matter everywhere and almost no antimatter.
4. How do we know that the sun isn't made of antimatter and we're made of matter and we're just lucky that we haven't yet touched the sun? The sun spews out particles constantly—mostly protons—in the solar wind. If they were anti-protons, there would be antimatter explosions all the time, but we don't see that. We know the sun is not made of antimatter.
5. How about other stars in our galaxy? Not only our galaxy, but even the space between galaxies, is filled with a gas, mostly hydrogen, a little helium and lithium, and other light elements. Astronomers can see light being absorbed and emitted by this gas. It also appears to be matter because cosmic rays pass through it and we don't see matter/antimatter explosions.
6. We return to the original question: Why are we here? Apparently, there's something special about matter in relation to antimatter. This is really the motivation for studying fundamental physics. An understanding of the difference between particles and anti-particles can help explain the cosmic fact that we are here.

H. Scientists have made measurements in these kaon systems starting in the 1960s and ever since and found that there is an asymmetry in the universe between matter and antimatter. That finding goes in the right direction to explaining why there is a little bit more matter than antimatter, but it doesn't go far enough. The numbers don't work out.

I. If we work out how much matter and antimatter should be left over today from the Big Bang, based on the standard model, we cannot account for the amount of matter that exists so it's still something of a puzzle. Physicists are setting up accelerator experiments to look at modern versions of this kaon decay.

III. Let's look at some other experiments that are going on today that give a sense of the kinds of topics physicists are interested in.

A. I've talked a lot about the solar neutrino puzzle and the desire of particle physicists to understand whether neutrinos have mass and whether they oscillate.

1. The accelerator at Fermilab is used in experiments that are different from those involving big tanks buried in mines. In this research, protons are smashed into a target and the resulting spray of particles is examined. Many of these particles are pions and kaons and particle/anti-particle pairs.
2. Next, magnets are set up to sweep most of the particles out of the way and leave behind a beam of, for example, positively charged pions. The energy of that beam can be controlled by tweaking the energy of the accelerator and the strength of the magnet.
3. Pions decay, and one of the results of that decay is neutrinos. The pion beam creates a beam of neutrinos, as well as electrons, muons, and other particles. If you smash these particles into a target—a

wall that is 200 feet thick of steel and concrete—they are absorbed, and they come to a halt. Nothing comes out the other side of the wall except a beam of neutrinos.

4. The direction and energy of this beam can also be controlled, as can the flavor of the neutrinos. Instead of waiting for low-energy neutrinos from the sun to come and hit our detectors, we are actually able to produce many neutrino events.

B. Another topic of interest in particle physics is the ability to build higher energy machines. This has been a quest since the origins of quantum mechanics, because the higher the energy that can be achieved, the finer the microscope that results.

1. Some scientists are beginning to do research on the "next linear collider." The idea is to accelerate electrons and anti-electrons or muons and anti-muons in a giant linear machine.
2. Brookhaven has also recently built a machine, the *relativistic heavy ion collider* (RHIC), used to study both nuclear and particle physics. The idea of RHIC is to accelerate large particles, such as lead nuclei, into each other. The result is something like a pancake filled with quarks and gluons. The prediction of the standard model is that we may actually form a new state of matter, a quark-gluon plasma with certain fairly simple properties.

C. We also see developments in physics that do not involve accelerators. Some researchers are returning to the physics of the 1920s and looking at cosmic rays.

1. Cosmic rays come from a variety of sources, not just the sun. In fact, we're not even sure where all the cosmic rays come from. They might be from supernovas; they might be from some very energetic, exotic phenomena at the center of galaxies.
2. We do know that cosmic rays are high-energy particles, mostly protons, that strike the earth's upper atmosphere, producing some kind of nuclear reaction. A proton strikes against a nucleus and produces some particles, which in turn, strike other nuclei in the atmosphere, which in turn, strike others, resulting in a shower of particles.
3. We've observed that the higher the energy you go to in looking for cosmic rays, the fewer events you get. If we wait long enough, however, we occasionally see a cosmic ray event of stupendous energy, along the lines of 10^{20} eV—billions of times more energy than we can produce.
4. Nature gives us this particle accelerator, but the bad news is that we have to wait for it and we don't know when or where it will occur. Detectors for these occurrences are built in out of the way places, such as in the desert or under the Antarctic ice sheet.
5. These ultra-high-energy cosmic rays are interesting both to cosmologists, who want to learn about the astrophysical phenomenon that produces them, and to particle physicists, who want to know what will happen in a particle physics event with 10^{20} eV of energy.

IV. We could go on about particle physics and astrophysics and experiments being performed today that boil down to looking for high-energy physics, trying to solve the puzzles in the standard model. Your job in the future will be to connect the exotic experiments and results you hear about with the elements of the standard model that we've constructed in this course.

Essential Reading:

Kane, *The Particle Garden*, Appendix C.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 2.11.

Recommended Reading:

Riordan, *The Hunting of the Quark*, chapter 16.

Lederman, *The God Particle*, chapter 7, section on "Slightly broken symmetry."

Wilczek and Devine, *Longing for the Harmonies*, chapter 27.

Questions to Consider:

1. If an astronomer looks at a distant star, is there any way she can tell whether the star is made of matter as opposed to *entirely* of antimatter? (If not, how could we conclude that the universe is mostly matter and very little antimatter?)
2. If a physicist is interested in learning about neutrino oscillations, what are the primary advantages of using an accelerator-generated neutrino beam, rather than just looking at the naturally produced (and enormously abundant) solar neutrinos?

Lecture Twenty-Two

Back to the Future (2)—Puzzles and Progress

Scope: If the standard model is such a great success, why are many physicists looking beyond it for some deeper and more fundamental theory of nature? Their reasons fall into the categories of practicality, aesthetics, and mathematics. None of these is, by itself, convincing proof that such a deeper theory exists, but taken together, they make it hard to believe that we're at the end of the line. Where are we headed next? We must begin with the missing link of gravity. We'll talk about issues of simplicity, unification, and grand unification. Then, we'll look at two conceptual developments that, to many physicists, seem to be the best candidates for new physics. We'll look at both supersymmetry and the new and highly promising theory of strings.

> I know that this defies the law of gravity, but, you see, I never studied law.
>
> —Bugs Bunny

Outline

I. In the last lecture, we talked about the directions that particle physics is taking in the world of experiments. In this lecture, we'll see that theorists are also looking to go beyond or beneath the standard model. We have several theoretical hints that the standard model, beautiful and successful as it is, is not the final story. In fact, for a number of reasons, it can't be.

- **A.** You may have noticed that I have left one topic—gravity—out of this story almost throughout the course. Gravity is a fundamental force of nature and the one that is most obvious to us.
  - **1.** Newton's description of the force of gravity was fairly simple and, over the years, quite successful. In 1915, Newton's theory was deepened by Einstein with the general theory of relativity.
  - **2.** Newton's theory left open the question of why the force of gravity is present between two massive objects, but Einstein gave us a geometrical picture of space-time that allowed us to understand this attraction.
- **B.** You might think that we could merge these two theories—the standard model of particle physics, which explains all the forces of nature except gravity, and the general theory of relativity, which includes gravity. The result would be a complete description of the world.
- **C.** The problem, though, is that Einstein's general theory of relativity is inconsistent with quantum mechanics. It is not a quantum field theory; it's a classical theory of nature.
  - **1.** Gravity does obey relativity, which is necessary for any correct theory of nature as far as we know today, but it doesn't, for example, satisfy the Heisenberg uncertainty principle. There is some mathematical contradiction between general relativity and quantum physics.
  - **2.** Gravity hasn't played a significant role in our study, because it affects only big objects. In fact, despite the attraction that we feel on earth, gravity is the weakest force. The attraction of individual atoms is miniscule, but it adds up so that we feel the force.
  - **3.** Think of a hydrogen atom. It has a proton and an orbiting electron. The electron is held in orbit by an electrical attraction. Electricity is not a particularly strong force of nature, but if we compare the electrical attraction of the electron to the proton with the gravitational attraction, the ratio is 10^{36}.
  - **4.** That tiny effect is almost unnoticeable, and it's also why physicists have not really addressed the idea that gravity is inconsistent with quantum mechanics.
  - **5.** Some particle physics theorists, however, have begun to wonder if a fundamental theory of nature can be found that would be consistent with both quantum mechanics and general relativity.
  - **6.** The study of black holes, for example, requires such a connection. Black holes are particle-like, involving quantum mechanics, but they're also heavy, which brings in gravity. The same is true for the study of cosmology. Once again, the distance scales are incredibly small, but the energy density is very high.

II. Let's turn to another topic, called *supersymmetry*, that theorists are exploring to try to come up with a deeper theory of nature.

- **A.** We have found and worked out all the possible geometrical symmetries that are available in space-time, such as translational symmetry, parity, and matter/antimatter symmetry. They are all either realized or broken in some way, but they're all relevant in the theory of gravity or particle physics, except for one, supersymmetry.
- **B.** We can think of supersymmetry as analogous to matter/antimatter symmetry, that is, as a "pretty good" symmetry of nature.
  - **1.** Imagine a symmetry between fermions and bosons. Remember the difference between these two: Fermions—electrons, protons, and quarks—are like particles; they don't sit on top of each other. Bosons, such as photons and the other force carriers, will sit on top of each other.
  - **2.** What if these two kinds of particles were completely symmetrical? What if there was some intimate connection between them, just as there is an intimate connection between protons and anti-protons?
  - **3.** This is the question of supersymmetry: Does every particle have a partner that has a different spin but is otherwise almost the same? We know that a top quark has an anti-partner, the anti-top quark, but does it have a supersymmetric partner? We currently have no evidence for super partners for any of the existing particles.
  - **4.** The names for these partner particles, if they're discovered, will be whimsical. For the fermions, the partner of a quark will be a *squark* and the partner of a top quark will be a *stop squark*. For the bosons, the partner of a photon will be a *photino*, and so on.
- **C.** Theorists have begun working out the mathematical consequences of supersymmetry and made some interesting discoveries.
  - **1.** They've discovered, for example, that if supersymmetry exists, we can add it to the standard model. In fact, the model tells us a little bit about the behavior and properties of these particles.
  - **2.** For example, we would expect to produce these particles at an energy of around a trillion eV. Our next generation of particle accelerators at Fermilab and the large hadron collider in Europe should be able to produce supersymmetric particles if they exist.

III. Probably the most exciting explorations in the world of theoretical particle physics are in the complex field of *string theory*.

- **A.** Let me try to give you an idea about string theory by asking: What is the single most fundamental idea of particle physics? Your answer might be that the world is made of particles.
- **B.** That's what particle physics is based on. QCD and the electroweak theory postulate a world filled with point-like objects. We can't visualize a point because it is a mathematical entity, but we can attribute certain properties to it, such as charge, mass, and spin. We can then make calculations about these particles according to the rules of quantum field theory.
- **C.** String theory asserts that perhaps the world is not made of points. Maybe the fundamental constituents, the building blocks, are actually little lines or strings. A constituent might be a little line with two ends, or a closed loop, like a doughnut.
- **D.** The most significant aspect of this theory is that it would allow the whole universe to be understood in terms of just one string. In string theory, we don't have many different kinds of fundamental particles. There is only the string, and all objects are made of string. The theory is as unified as it could possibly be.
  - **1.** An up quark might be thought of as a string that vibrates in a particular pattern. A different, more energetic pattern might be a charm quark.
  - **2.** The forces, too, would be understood to come from the string.
- **E.** String theory also addresses the problem of renormalizability in the standard model.
  - **1.** Remember that some calculations in particle physics result in mathematical infinities that must be renormalized. In string theory, there are no such infinities.
  - **2.** The infinities in the standard model spring from the assumed existence of physically point-like particles. Points can get arbitrarily close to each other, and the closer they get, the stronger the fields become. If the particles are infinitely close, the calculations can go all the way to the limit of infinite fields. Strings, however, spread out over some distance, which can never get any smaller than the size of the string itself.

F. What is a string made of? String theorists postulate the existence of a string, but it's not made of anything. It is not, for example, made of "string atoms," which would be fundamental particles.

G. How do strings interact?

1. In the current standard model, we can imagine two particles interacting as they move along and creating, spontaneously, a virtual photon that travels between them.
2. In string theory, two strings move along and, at a certain point, they come together. Perhaps they sort of fold together to form one larger string for a brief moment, then that one string might split apart again into two strings. That might be the interaction of two fundamental particles.
3. In our contemporary language, the intermediate state describes particles and virtual particles, but in string theory, there was never anything but strings interacting. Further, there are never any infinities because the size of the string is limiting.

H. What is the size of a string? String theorists can actually put a number on it, a number that comes from another idea that is bothersome in particle physics.

1. Remember that the electric and weak forces are unified at a high energy scale—trillions of eV. But also recall that we have not yet determined whether the strong force is unified with electricity and the weak force. Right now, we assert that the forces are different, but might they, in fact, merge together at some ultra-high energy?
2. Once scientists thought about this *grand unification*, they also wondered about the inclusion of gravity. We can even estimate the energy at which all these forces might come together, which is about 10^{19} GeV.
3. Quantum mechanics says that an ultra-high-energy scale corresponds to a tiny distance, and that's the size of the string.

IV. String theory offers the possibility of an ultimate unified theory in which all physical observables can be computed from a mathematical framework.

A. In working with the mathematics, we have found that supersymmetry is a consequence of string theory. The theorists are, in a sense, making a prediction about the existence of supersymmetric particles, which begins to place the theory in the realm of physics.

B. String theory also predicts the theory of general relativity as a low-energy effective theory. That is to say that the mathematics of strings predicts Einstein's general theory of relativity.

C. Finally, string theory has some strange aspects. For example, in order to make the theory mathematically consistent, it has to be true that strings live in more than three spatial dimensions. That would mean that other dimensions exist that we haven't noticed yet.

D. String theory has the potential to be the greatest revolution in physics since the discovery of relativity and quantum mechanics. It is not yet fully developed, but it is definitely a topic to take note of.

Essential Reading:

Kane, *The Particle Garden*, chapters 9–11.

Weinberg, *Dreams of a Final Theory*, chapter IX.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapters 9.3–9.5.

't Hooft, *In Search of the Ultimate Building Blocks*, from chapter 22 on.

Recommended Reading:

Greene, *The Elegant Universe*, Part III. (A great book—take your time and read the whole thing!)

Lederman, *The God Particle*, first half of chapter 9, through the section on superstrings.

Calle, *Superstrings and Other Things*, chapter 25, sections on "GUTS" and "Superstrings."

Krauss, *Fear of Physics*, chapter 6.

Wilczek and Devine, *Longing for the Harmonies*, Tenth Theme.

Questions to Consider:

1. Given the successes of the standard model and the arguments that something may exist "beyond" the standard model, what are your feelings about looking for such new and exotic physics, requiring significant commitments of taxpayer-supported funding and physicists' time?
2. Look up the size (length) of a superstring. How many times smaller than a proton is that? Can you make up some kind of analogy in the form "String size is to a proton as proton size is to _________"?
3. What would you call the supersymmetric partner of each of the quarks? (Remember the top's partner is the *stop*) Can you pronounce them all?

Lecture Twenty-Three

Really Big Stuff—The Origin of the Universe

Scope: Cosmology, the study of the universe as a whole, relates to particle physics, because matter at the very largest scales requires understanding of matter at the very tiniest. In this lecture, we examine the Big Bang scenario and see how it fits into the standard model. We also explore the relationship of *inflation* to the cosmos and define the latest buzzwords in physics, *dark matter* and *dark energy*. We'll talk about data from the COBE satellite mission and more recent astrophysical observations that teach us about the early universe and the connections between cosmic structure and the microscopic world.

> The statement that the Universe arose from inflation, if it is true, is not the end of the study of cosmic origins—it is, in fact, closer to the beginning. The details of inflation depend upon the details of the underlying particle physics, so cosmology and particle physics become intimately linked together.
>
> —Alan Guth

Outline

I. This lecture looks at cosmology, the study of the structure of the universe.

- **A.** Cosmology may seem unrelated to particle physics; one is the study of the largest possible system and the other, the study of the tiniest. Surprisingly, these two branches of physics are intimately connected.
- **B.** The Big Bang that may have begun the universe was a high-energy, high-temperature event. Because high energies correspond in quantum mechanics to small distances, the universe was in some sense tiny at the moment of the Big Bang. We need to understand the rules and constituents at the particle level to learn where the universe began and where it is going.

II. Let's begin with the Big Bang, a theory that has been around for a long time. Why do we believe in this theory for the origin of the universe?

- **A.** First of all, imagine that you're an astronomer looking at stars. If we lived in a static universe—a universe that's very large, possibly even infinite, and has been here forever—then you would expect to see many stars, all of them moving in different directions. You should be able to determine the speed of stars, which we can using the Doppler effect, and find some sort of distribution of velocities among the stars.
- **B.** If we start looking at distant objects, such as stars in galaxies, they all appear to be moving away from us, and the greater their distance, the faster they seem to be moving away.
- **C.** A simple explanation exists for this effect, but it requires an abstract conception of the universe.
  1. Let's think of the universe as two dimensional. Imagine that we live on the surface of a giant ball, like a big balloon, and we are ants crawling on the surface. This conception reduces our universe to two dimensions, which curve around in the shape of a ball.
  2. If our balloon is being blown up and expanding, then all the spots on it are moving apart. Every individual ant is moving away from every other individual ant on the surface of the balloon.
  3. If you could put yourself in the worldview of one of those ants, in every direction, you would see other ants moving away from you, and the farther away they are, the faster they move.
- **D.** We know that our universe is expanding and that the stars are moving away from us. If we run the clock backward and plug in some numbers, such as the speed and distance of these stars, we can calculate how long ago it was when that far-off galaxy we're looking at was right next to us. The answer is about 15 billion years ago.
- **E.** We can do similar calculations for other galaxies, and we arrive at the same answer. Every galaxy, every star that is distant from us now, appears to have been very close to us about 15 billion years ago.
- **F.** We know, then, that 15 billion years ago, the universe was in a highly compressed state. Further, all the energy of the universe was there from the beginning. Energy is conserved, which means that the universe had its origins in a very tiny, very energetic situation that resulted in the Big Bang.
- **G.** How might we demonstrate that this theory is true?

1. If the Big Bang occurred, we should be able to see the aftereffects, such as light and radiation. Using the laws of thermodynamics, we should also be able to predict the temperature of the residue of this explosion now, 15 billion years later.
2. The first such observations were made in the 1960s by Pensius and Wilson, who detected radiation coming toward us from all directions in deep outer space. This *cosmic microwave background* is no longer very hot. The universe has cooled down so much that the radiation is very long wavelength.

H. Another piece of evidence for why we might believe in the Big Bang theory can be found in the dust between the stars and the galaxies.

1. The early universe was, essentially, an accelerator experiment with very high energy and very high densities. We should be able to calculate what was produced in this accelerator, including the particles and the heavier elements.
2. The amounts of heavy elements produced should be relatively small, because the explosion was very brief. In looking at the dust in the universe, astronomers have determined that the material is precisely what we would calculate from the Big Bang scenario.

III. Let's take a moment to discuss what's going on today in cosmology as a result of data received from satellites.

A. Cosmic background radiation is turning out to be a wonderful tool to learn about the Big Bang. The Cosmic Background Explorer (COBE) was the first satellite to collect information on this phenomenon.

1. COBE went up in the late 1980s and made measurements that fit beautifully with theoretical expectations.
2. For example, radiation in different parts of the sky was observed to be almost identical. Remember that we're looking back in time; this identical radiation was emitted 15 billion years ago and is now traveling toward us from all directions.

B. Let's also think about variations in density in the universe.

1. The universe is divided up into "clumps," with a galaxy here and a galaxy there and nothing in between. Where do these galaxies come from? Presumably, a galaxy is some region of dust and gas that coalesced by gravity and began to form stars.
2. The differences in density are explained by similar differences in the early universe. Regions that were a little more dense at that time began to attract material and, thus, became even denser.
3. The data reveal that this model of galactic formation is consistent with what must have taken place in the early universe to have a later universe that is clumped into galaxies, as ours is.

C. Other research in cosmology is looking at *dark matter*, a substance in outer space that doesn't glow.

1. Every galaxy has some outlying stars that are almost always in some kind of orbit. By making careful measurements, we can deduce the speed and orbital path of those stars, as well as the mass in the middle that is causing the orbit.
2. If we calculate that mass, we conclude that something else exists inside the galaxy that is not glowing but is gravitating.
3. We don't quite know what this *dark matter* is. It may be yet-undiscovered particles, such as supersymmetric particles.

D. Another phenomenon that has been observed recently and is even more mysterious than dark matter is *inflation*. This phenomenon is related to what must have been occurring at the start of the Big Bang.

1. The Big Bang would have required a supply of energy that inflates the universe rapidly for a short amount of time. This inflationary scenario explains a number of other observations, including the fact that the universe looks so much the same in all directions.
2. Where would that energy come from? Possibly, from the Higgs (or a Higgs-like) field. If this field exists everywhere in the universe, it may have come from a kind of condensation after the Big Bang.
3. We imagine that the early universe, at the start of the Big Bang, was very symmetrical. All the theories were unified. The electric and the weak forces were the same in nature, and the Higgs particle had not yet condensed out. Then, as the universe expanded and cooled, the Higgs field condensed out.
4. When a gas condenses into a liquid, it emits heat. As the Higgs field condensed, it would release some form of latent heat, which is a supply of energy. That release of heat would pour energy into all the particles, which would then expand rapidly.

5. This scenario is consistent with particle physics and would explain cosmological inflation. Further, new data suggest that we are now undergoing another period of inflation; the rate of expansion is picking up as though some cosmic field is condensing and adding energy, which is called *dark energy*.

IV. We have evidence for a Big Bang about 15 billion years ago that involved an inflationary period and high temperatures. The goal of current research is to tie all these ideas together—string theory, standard model physics, and Big Bang cosmology—to form a coherent picture of the cosmos.

Essential Reading:

Kane, *The Particle Garden*, chapter 12.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, chapter 8.

Recommended Reading:

Lederman, *The God Particle*, second half of chapter 9, starting with the section on "Flatness and dark matter."

Weinberg, *The First Three Minutes*. (The whole book is good!)

Calle, *Superstrings and Other Things*, chapter 25, last two sections.

Wilczek and Devine, *Longing for the Harmonies*, chapters 4–6; Ninth Theme.

Questions to Consider:

1. Can you think of a method for estimating the age of the universe? How on earth can we know that it is (roughly) 15 billion years old?
2. Cosmic background radiation is the oldest light we can see. It was emitted when the universe was a few hundred thousand years old. (Any light emitted *earlier* than that existed in a universe dense enough that the light was reabsorbed.) If we cannot *see* anything from before that time, how can we *know* anything about the universe from before that time?
3. Does it make physical sense to ask, "What happened before the Big Bang"?

Lecture Twenty-Four

Looking Back and Looking Forward

Scope: What have we learned after more than 100 years of intense study of fundamental particles, and what puzzles still remain? What influence does particle physics have on our lives, on science, and on our philosophical worldview? We'll conclude this course with thoughts on what you might take away from this experience—a sense of physical order and an understanding of the constituents of the world. Remember that progress in science does not generally overthrow the old, but modifies and extends it, which means that you can use your understanding of the standard model as a framework in which to fit new knowledge and understanding.

> The quality of a society is indicated by the questions it asks. One of the questions is, what is man made of? The answer is matter, and it is the nature of matter that is the domain of High Energy Physics. The society that doesn't ask this question is a suffering society.
>
> —Sid Drell

> Scientific understanding has inherent cultural value. It has great beauty. It adds to the satisfaction of our lives.
>
> —Robert Wilson (to the Joint Committee on Atomic Energy quoted in *The World Treasury of Physics, Astronomy, and Mathematics*, p. 697)

Outline

I. In this final lecture, we will look back at everything we've been talking about and try to put it into a framework.

- **A.** First, let's ask, "What is the standard model of particle physics?" The idea of the standard model is that we can understand all the complexity and diversity of physical phenomena in terms of the point-like elementary particles from which all objects are made.
- **B.** These particles interact with one another through some fairly simple and well-understood forces—the electroweak force, the strong nuclear force, and gravity.
- **C.** Speaking generically, there are only two kinds of particles, quarks and leptons. The quarks are the strongly interacting particles that form protons and neutrons and a few more exotic particles that are found only in accelerator experiments or cosmological or astrophysical phenomenon. The leptons are the lighter ones, such as the electrons or the neutrinos that come out of the sun.
- **D.** This theory is as quantitatively successful as any scientific theory in any branch of science. Despite its success, however, the standard model is not the end of the story. Many puzzles and questions remain, even in the framework of the standard model itself.
- **E.** Sometimes, physicists talk about discovering a *theory of everything* (TOE), which would describe the true fundamental constituents and forces. From that basis, this theory would explain the quarks and the leptons and their interactions, and so on. In other words, this theory would explain the standard model.
  - **1.** The standard model explains how atoms are formed. An atom is quarks forming into protons and neutrons that bind together to form a nucleus, along with electrons, which are electrically attracted. The atom can be explained by the theories of QCD, to describe the nucleus, and QED, or the electroweak theory, to describe the attraction of electrons to the nucleus.
  - **2.** This theory explains how two hydrogen atoms can bind together and form a stable hydrogen molecule and how hydrogens and oxygens can combine to form stable water molecules. In principle, you start from this fundamental theory and work your way up to a deep understanding of chemistry, biology, and other sciences.
- **F.** Ultimately, what particle physicists are studying is the five conceptual ideas that tie together the physical world: force and energy, matter, and space and time. Those five ingredients are the ultimate components of particle physics.

II. We began this course by asking why people care about particle physics.

A. As we said, we can speak of spinoffs of particle physics. This branch of physics may be the one that is least related to our lives, but it has resulted in some of the most sophisticated, complex machinery ever designed, including equipment for medical diagnosis and treatment. Further, in a sense, the Web is a spinoff of particle physics.

B. Other spinoffs from particle physics are not technological, but intellectual, including the field theory itself. Quantum field theory is a general mathematical framework that forms the basis for doing calculations. It can be extended to describe interactions in a number of complicated systems, including those in biology and even economics.

C. Finally, we might note the reductionistic pleasure we find in studying particle physics and the idea that this study satisfies basic childlike curiosity.

III. What should you take away from this course?

A. The guiding idea here is that the world is orderly, made, at its core, of simple “ingredients” governed by simple laws.

B. To the best of all the data and observations we’ve made for the past 100 years, we’ve learned that the world is made of protons and neutrons, which form nuclei, with electrons around them. That picture will be deepened and broadened in the future, but it will not go away.

C. Your job in the future is to question the sensational scientific discoveries you hear about and tie them into the standard model.

1. If a supersymmetric particle is discovered, you’ll ask, “How are these particles related to ordinary particles? What have they done to the standard model? How have they deepened it? What do we understand now?”
2. You should also maintain your skepticism if you hear about discoveries that fly in the face of 100 years of data.

D. A new issue in physics research today is outreach. Physicists are being asked to make a greater effort to communicate their knowledge to the public. As you hear about these exotic ideas—string theory, dark matter, dark energy, extra dimensions—you are now equipped to make some sense of them for yourself.

Essential Reading:

Weinberg, *Dreams of a Final Theory*, chapter X.

Kane, *The Particle Garden*, chapter 7.

Schwarz, *A Tour of the Subatomic Zoo*, chapter 9.

Barnett, Muhry, and Quinn, *The Charm of Strange Quarks*, pp. 204–207.

Recommended Reading:

The bibliography contains some great selections; I encourage you to look there for interesting reading. (If you haven’t read anything by Feynman yet, I’d certainly recommend you pick up one of his.)

Questions to Consider:

1. What aspect of the standard model do you find most appealing, and what (if any) are you most certain will be replaced or improved upon?
2. As a final assignment, look for an article in a current magazine or on the Web that covers a development in particle physics that is *newer* than this course! How does it connect to what you have learned here? Does it change your perceptions of what you have learned?

Biographical Notes

A biographical list of "key contributors" to the development of particle physics is almost impossible, because the number of contributors is huge! Although famous physicists often get sole credit for their accomplishments, the great discoveries are inevitably part of a web of scientific progress. Truly significant contributions come from both brilliant and more mediocre scientists, not to mention the support from graduate and sometimes undergraduate students, technicians, lab assistants, and others. Most of the discoveries in physics have a complex lineage; historians can (and do) quibble about the attributions and origins of almost every idea in the field. Some ideas get "rediscovered" or further developed, then attributed to the one who was better able to spread the word. What follows is an extraordinarily abbreviated list of some of the most famous names in the field. The large number left out is painful to this "biographer"—especially the more recent contributors, whose number is large and growing.

To learn more, a starting point is with Nobel Prize winners. Even among this select group, I have left many out! The Nobel site, www.nobel.se/physics/ laureates, is a good starting place. (Another good site for more biographies is www.gap-system.org/~history/BiogIndex.html.) Of course, many of the reference texts for this course also contain extended biographies of various subsets of key players.

Niels Bohr (b. 1885, d. 1962, Nobel Prize 1922)

A Danish physicist who lived much of his life in Copenhagen, Niels Bohr is known as the first physicist who made the transition from classical to quantum understanding of atoms. He was infamous for his mumbling; many people recount stories of listening intently to the great Niels Bohr, only to have no idea afterward what he said. As a postdoctoral researcher, he worked briefly in Ernest Rutherford's lab starting in 1911. He expanded Rutherford's classical "solar-system" model of an atom into what is now known as a semi-classical, or hybrid quantum model. Quantum mechanics did not yet exist, but Bohr's model of the atom introduced many of the qualitative ideas of quantum physics and helped provide a stepping stone to the more fully developed theory of the 1920s and 1930s. Ten years later, Bohr helped create and direct the Institute of Theoretical Physics in Copenhagen (now known as the Niels Bohr Institute). Although Bohr himself did not make so many direct significant contributions to the quantitative development of quantum mechanics, his leadership, philosophy, and guidance were of essential and fundamental importance. Bohr helped develop ways of interpreting quantum mechanics; in fact, we now refer to the *Copenhagen interpretation* of quantum mechanics when discussing how to think about quantum physics. His famous debates with Einstein helped further establish quantum mechanics.

Marie Curie (b. 1867, d. 1934, Nobel Prize[physics] 1903, Nobel Prize [chemistry] 1911)

One of the most famous pioneers in the early days of modern physics and inventor of the term *radioactivity*, Marie Sklodowska left her native Poland in 1891 (where opportunities for advanced studies were extremely limited for women) to study math and physics in France. She married Pierre Curie in 1895, a like-minded, similarly energetic and brilliant scientist. Marie became interested in Becquerel's new discovery of "uranium rays" and decided to pursue a Ph.D. in this field. She maintained her fascination with radioactivity throughout her professional career. Curie was the first person to understand, based on her research, that radioactivity was not a chemical phenomenon, but linked to the atomic nucleus. She worked closely with her husband, Pierre (until his untimely death in a street accident in 1906), often in extremely difficult circumstances, arduously isolating, then studying radioactive elements, including polonium (which Curie named after her native Poland). She isolated a tenth of a gram of pure radium from literally tons of raw material, all worked and processed by hand. She received her Ph.D. in 1903, the same year she got the Nobel Prize! She received her second Nobel (the first person ever to do so) in chemistry, for her work in isolating and studying the radioactive element radium. (Her daughter, Irene, would later win the Nobel Prize in chemistry for the discovery of artificial radioactivity.) Marie Curie died of leukemia at the age of sixty-seven, possibly the result of massive exposure to radioactive materials during her career.

P.A.M. Dirac (b. 1902, d. 1984, Nobel Prize 1933)

Paul Dirac was an extraordinarily brilliant man, raised in England with a Swiss father and British mother. He was a man of few words. As a child, his father insisted that only French should be spoken at the dinner table. As a result, Dirac never said much! Acquaintances joked that his vocabulary was "yes," "no," and "I don't know." Still, his papers were beautifully written; he was inspired by the beauty of mathematics. He had eleven papers in print by the time he got his Ph.D. at age twenty-four. Along with developing the new theory of quantum mechanics, Dirac struggled with combining relativity with quantum mechanics; he wanted his quantum equation to satisfy Einstein's

special theory of relativity. The Dirac equation is an elegant mathematical marriage of those two theories. This equation predicted the existence of antimatter, which was later experimentally discovered.

Dirac worked briefly with Bohr as a postdoc in 1926 and received his Nobel Prize in 1933 (along with Schrödinger). His mother went with him to Stockholm; he was thirty-one at the time. Dirac made a large number of other significant contributions during his career, including the introduction of an extraordinarily powerful mathematical notation, now called *bra's* and *ket's* for the little brackets he used, which is indispensable in practical quantum mechanical calculations. Dirac held the Lucasian chair of mathematics at Cambridge University (held earlier by Isaac Newton and, currently, by Stephen Hawking) for thirty-seven years.

Albert Einstein (b. 1879, d. 1955, Nobel Prize 1921)

Born in Germany, Einstein is surely the most brilliant and famous physicist of the twentieth century. (There are countless biographies available; I would urge you to read more about this fascinating man. His own writings are often surprisingly accessible, as well.) His contributions to physics are extraordinarily broad and far-ranging and, in several cases, profoundly changed the way we conceptualize the physical world. In 1905 (his "miracle year"), Einstein was a young man working in a patent office, doing physics in his spare time; he had not been able to secure a university position. He published three papers that year, any one of which would have put him on history's top ten list of physicists. One of those papers was on the special theory of relativity, which changed our understanding of the nature of space and time. Another was on Brownian motion, a paper that effectively put to rest the longstanding debate, both physical and philosophical, regarding the existence of atoms. The third was on the photoelectric effect, which was in a real sense the birth of quantum mechanics. That paper extended and generalized Max Planck's ideas. Einstein was the first to appreciate the true depth of the idea that photons are quanta, or "chunks," of energy. (Technological applications of this concept abound today, from electric eyes to solar panels.) Roughly ten years later, Einstein published his work on general relativity, in which he explained and described a theory of gravity that once again revolutionized how we conceive of space and time.

In his later life, Einstein struggled to find a grander "unified theory," with no success. He also argued frequently against the quantum theory that he had helped give birth to, saying famously, "God does not play dice with the universe." This was not a religious commentary, but a statement that he found the random nature of quantum mechanics philosophically unacceptable. Although he was, in the end, demonstrably wrong in this attitude, his constant questioning of the then-young theory of quantum mechanics played an important role in its early development.

Enrico Fermi (b. 1901, d. 1954, Nobel Prize 1938)

Enrico Fermi was an Italian physicist, famous as perhaps the last physicist who was both a brilliant experimentalist and world-class theorist. Fermi paved the path to nuclear power (and weapons) and, along the way, played a central role in the development of both quantum mechanics and nuclear physics. Fermi's self-confident but casual and open style was in sharp contrast with the somewhat elitist approach of German physicists of that era and heavily influenced the following generation of physicists, many of whom worked or studied with him. (Fermi was also famous for his "Fermi problems," realistic puzzles involving logic, numeracy, and basic physics principles; his ability to make quantitative estimates of the solution to such vague but real-life problems was truly impressive.)

The number of physics terms with *Fermi* as an adjective is mind-boggling: Fermi constant, Fermi statistics, Fermions, the Fermi (a unit of length, roughly the size of a proton, 10^{-15} m), Fermi gas, Fermi sea, Fermi energy, Fermi momentum, Fermilab, Fermium (element number 100 in the periodic table), and the list goes on. Fermi named the neutrino and developed the first mathematical theory of the weak interaction (beta decays). He studied the physics of neutrons early in his career and pions, later. He escaped fascist Italy (his wife was Jewish), using his Nobel Prize in 1938 as a tool to emigrate to the United States. Once there, he worked on experiments that led to the first successful controlled nuclear chain reaction (under the sports stadium at the University of Chicago!). After the war, he fought the development of the H-bomb on ethical grounds. Fermi died very young, of cancer, still in his prime as a physicist.

Richard Feynman (b. 1918, d. 1988, Nobel Prize 1965)

Born and raised in New York and one of the most engaging and charismatic figures in recent physics history, Richard Feynman can be characterized, in my opinion, as the greatest physicist of the second half of the twentieth century. Irreverent, egotistical, brilliant, a true scholar and teacher, Feynman made contributions to a wide variety of

branches of physics. His Nobel Prize work was for the development of QED, the quantum theory of light. One of the great aspects of that work was his invention of the *Feynman diagram*, a simple cartoon-like sketching device that represents a quantitative mathematical formula. These diagrams are ubiquitous now, not just in QED but in almost any branch of modern physics, allowing one to think qualitatively about complex physical processes while retaining the mathematics "underneath" the pictures. Feynman played a central role in the ongoing development of particle physics after QED, including his insightful interpretation of high-energy data from SLAC (the Stanford Linear Accelerator) in terms of *partons*, later to become quarks.

A number of biographies of Feynman are available (see the Bibliography). His own writings on physics are inspiring and delightful. In the 1960s, Feynman decided to "rewrite the book" on freshman physics. The result, his famous *Feynman Lectures*, is on the shelf of almost any professional physicist. However, by his own admission, the lectures were not a complete success with the CalTech freshmen for whom he had intended them. (His autobiographies may annoy you because of his ego and occasional lack of respect for others, but if you can get past that, they are fascinating and entertaining.)

Murray Gell-Mann (b. 1929, Nobel Prize 1969)

Murray Gell-Mann a professor first at Chicago, then at CalTech, was a prime driver in our understanding of the strongly interacting particles, the quarks. A colleague of Feynman, Gell-Mann's style was quite different; Gell-Mann was literate and a bit sophisticated in his tastes, wearing fine clothes, but still with a great sense of humor and whimsy. His broad interests led one colleague to say, rather facetiously, "Murray has no particular talent for physics, but he's so smart he's a great physicist anyway." He invented the concept of *strangeness*, later understood to signal the presence of a new, heavier form of matter (the *strange particle*). He developed a mathematical framework based on symmetry, which he called the *eight-fold way*, to explain the properties of the rapidly expanding "zoo" of particles being discovered at accelerators in the 1960s. (The name was borrowed from Eastern mystical teachings, a reference that Gell-Mann later came to regret when his rigorous mathematical theories were sometimes misinterpreted as esoteric or philosophically vague.) Gell-Mann's development of the consequences of nuclear symmetries led to his articulation and naming of the *quark model*, which forms the underpinnings of our modern theory of QCD (quantum chromodynamics, the theory of the strong force.) His choice of particle name came from James Joyce's *Finnegan's Wake*, with a passage beginning "three quarks for Muster Mark!"—an appropriate name for what seemed, at the time, like a perfectly absurd particle of nature.

Werner Heisenberg (b. 1901, d. 1976, Nobel Prize 1932)

A German physicist who was the first to create a mathematical theory of quantum mechanics at the young age of twenty-three, publishing the work in 1925. Heisenberg argued that a theory should refer only to quantities that can be *observed*, an idea that played a guiding role in the development of quantum physics. Heisenberg was very much a mathematician; he nearly failed to get his Ph.D. because of his weakness with laboratory work. He joined Niels Bohr's Institute in 1926 for a productive year. In 1927, Heisenberg developed his famous *uncertainty principle*, which states that one cannot, in principle, have precise simultaneous knowledge of the momentum and position of a particle. (This principle is, in fact, a rigorous, mathematically derivable statement that contains useful quantitative, predictive power. It is far more than just a curious philosophical idea.) During World War II, Heisenberg spent five years directing the unsuccessful German atomic bomb project, a period in his life which remains somewhat controversial. (There has even been a recent Broadway play about this.) He was imprisoned by the allies briefly after the war but was returned to Germany in 1946, where he established the Max Planck Institute and served as its director until his retirement.

James Clerk Maxwell (b. 1831, d. 1879)

A Scotsman, born without privilege or high social rank, Maxwell worked in the field of mathematical physics, and electricity and magnetism, during the 1800s, when the scientific community was tackling this "exotic" field with great vigor. Maxwell was especially intrigued by the discoveries of Michael Faraday (himself a man with humble beginnings) who had introduced the concept of *force field* as a physically relevant entity. Maxwell succeeded in mathematically describing *all* phenomena of electric and magnetic origin in a set of four relatively simple equations, now called *Maxwell's equations*. Most of those had been developed over the previous decades by others, but Maxwell organized and formalized them, adding a key component based not on experiment, but on his own aesthetic mathematical sense of symmetry, intimately and permanently unifying electricity and magnetism. Maxwell

discovered that these equations led to the phenomenon of *traveling electromagnetic (EM) radiation*—moving at the speed of light—and with this, realized the deep connection to optics, as well.

Today, Maxwell's equations and the corresponding unification of forces are regarded as one of the grand highlights of human intellectual achievement. They form the basis of electrical engineering and modern optics and have survived the discoveries of modern physics in the twentieth century essentially unscathed. They paved the way for the discovery of relativity (being fully relativistic equations, even though Maxwell didn't appreciate that!) and form the classical underpinnings of QED, the quantum theory of light. The study of Maxwell's ideas generally forms the second half of any standard college-level introductory physics course.

Isaac Newton (b. 1643, d. 1727)

The father of physics, indeed of all modern science. In many ways, I can think of few individuals of the last 1000 years who had more direct and profound influence on the human condition. Isaac Newton's masterwork, the *Principia*, articulated not only a number of physical laws, but also the scientific method itself. Newton's laws describe and explain motion and gravity. When faced with the need to solve the equations he developed, Newton *invented* the calculus required to solve them. Newton's central laws are *universal*, applicable to any system in any circumstance. Even today, their accuracy and power is extraordinary. Although Newton's laws must be extended under extreme conditions (such as for objects traveling near the speed of light), they still form the basis for much of modern technology. Newton did both theory and experiment; his research touched and formed the roots of many branches of modern physics, including optics, thermodynamics (heat), fluids, and more. Students in freshman physics learn about Newton's work in their first semester (then repeatedly, with further depth, as they progress). The metric unit of force, the *Newton*, is named in his honor. Newton was not a pleasant or easy man. He had a big ego, never married, and had many disputes over intellectual priorities during his life. However, in an uncharacteristic but famous quote, he said, "If I have seen further, it is by standing on the shoulders of giants."

Emmy Noether (b. 1883, d. 1935)

Although not a physicist, this mathematician played a significant role in the early conceptual understanding of modern theoretical physics. Born and raised in Germany, Noether persevered in a system heavily biased against women in academia. She studied mathematics at university but was only allowed to sit in on classes unofficially. Even then, professors had to give permission individually. She studied under some of the great mathematicians whose names are also linked with developments of modern physics: Hilbert (whose work is now applied in quantum mechanics), Klein (general relativity and field theory), and Minkowski (special relativity). Noether later did her Ph.D. work with a mathematician whose work would also become closely tied to future physics developments, Paul Gordon (quantum mechanics and gauge field theories). Normally, such a brilliant and promising student in Germany would get a still higher degree ("habilitation"), but this was forbidden for women at the time. Noether helped her father, also a mathematician, and continued working, doing research, and supervising doctoral students, all without pay. (Hilbert, in attempting to get her a faculty position, said, "I do not see that the sex of the candidate is an argument against her admission as Privatdozent. After all, we are a university and not a bathing establishment.") Noether's publication list and reputation grew rapidly, but it took twelve years until she successfully petitioned to obtain the habilitation.

In 1915, she published the work that is most directly relevant to particle physicists, now known as *Noether's theorem*. Albert Einstein praised this work, calling it "penetrating mathematical thinking." The bulk of Noether's further research was in a field known as abstract algebra, which has also played a role in quantum mechanical theory. By 1922, she started receiving a small salary but was still without tenure. (Noether was also a Jew, a Social Democrat, and an outspoken pacifist, none of which was much help in that regard.) She left Germany in 1933 for the United States, as a result of Nazi dismissal of Jewish faculty. She spent several years teaching and working as a visiting professor at Bryn Mawr in Pennsylvania. Emmy Noether died quite young, of complications after a surgery. Albert Einstein, in a tribute to Noether in the *New York Times* on May 5, 1935, wrote:

> In the realm of algebra, in which the most gifted mathematicians have been busy for centuries, she discovered methods which have proved of enormous importance… Pure mathematics is, in its way, the poetry of logical ideas… In this effort toward logical beauty, spiritual formulas are discovered necessary for deeper penetration into the laws of nature.

Wolfgang Pauli (b. 1900, d. 1958, Nobel Prize 1945)

Born in Vienna, Wolfgang Pauli was in many respects the theoretical leader of the development of quantum mechanics in the 1920s and 1930s. Pauli even impressed Albert Einstein when, in his sophomore year in college, he published a brilliant review article explaining special relativity for a mathematical encyclopedia. Pauli spent a year with Bohr in Copenhagen (1922–1923) and, soon after, developed his famous "Pauli exclusion principle," which states that no two quantum particles (of spin 1/2) may exist in the same quantum state. This law of nature has tremendous applications. It explains, among many other things, the chemistry and properties of the periodic table of the elements and the structure of atomic nuclei. In 1931, Pauli predicted the existence of a new particle of nature, later called the neutrino, although it was several years before he would actually publish a paper about it. Pauli was always a sharp thinker and, ever skeptical, able to poke holes in anyone's theory. He was quite intolerant of sloppy thinking, striking fear in the hearts of visiting speakers when he sat in the front row. He is famous for his quips, such as stating that a paper was "not even wrong." To a postdoc, he once said, "I don't mind your thinking slowly. I mind your publishing faster than you think." Still, for his brilliant, critical, and honest thinking, Pauli has been called by some "the conscience of physics."

Max Planck (b. 1858, d. 1947, Nobel Prize 1918)

A German physicist who started his career studying thermodynamics (heat), a branch of physics that was well established by the late 1800s. When Planck entered university at age sixteen, he was told that physics was essentially a complete science with little prospect of further developments. Fortunately, he decided to study physics despite the bleak future for research that was presented to him! He got his Ph.D. by age twenty-one. Planck's fame arises from his work on the question of electromagnetic radiation emitted by hot objects. It had been established that classical physics (Maxwell's equations, combined with thermodynamics) not only couldn't explain the data but also gave nonsensical, infinite results. After what Planck called "the most strenuous work of my life," he was able to describe the data by postulating that electromagnetic radiation was *quantized* in its interaction with matter, following a characteristic formula he derived. ($E = hf$, which states that the energy of a bundle of light is a constant, h, times the frequency of the light). This was the birth of quantum mechanics. The idea that energy comes in chunks, or bundles, *quanta*, was a stroke of genius, a thoroughly nonclassical and unexpected concept. Interestingly, Planck's contributions to quantum theory didn't continue after this and, in fact, he was not convinced by the developments in quantum theory that arose from his work. The constant h that appears in the equation he developed, and in essentially all quantum mechanics formulas since, is now named *Planck's constant*, in his honor.

Ernest Rutherford (b. 1871, d. 1937, Nobel Prize 1908)

Born in New Zealand but living his life in England, Rutherford was a brilliant experimentalist, the first of the modern breed of particle physicists. He was a bear of a man, with a loud voice and a strong personality. Working at the Cavendish Laboratories, Rutherford was the first person to identify the types of radiation emitted by naturally radioactive substances. He recognized that radioactivity represented the transformation of elements from one type to another. Rutherford's experiments with Hans Geiger and Ernest Marsden (an undergraduate) helped him formulate the classical but thoroughly modern picture of an atom as a composite object with a tiny, heavy nucleus at the center and electrons in orbit. His famous quote about this experiment is: "It was quite the most incredible event that ever happened to me in my life. It was as if you fired a 15-inch artillery shell at a piece of tissue paper and it came back and hit you." Rutherford later showed that he could send alpha particles onto nitrogen and convert atoms into oxygen, the first deliberate "transmutation of elements" accomplished by humans. In his later life, Rutherford remained active, administrating the Cavendish Labs and guiding many future physicists in their early careers. Shortly before his death, Rutherford said, "Anyone who expects a source of power from the transformation of these atoms is talking moonshine." (The first nuclear chain reaction was constructed shortly after his death.)

Abdus Salam (b. 1926, d. 1996, Nobel Prize 1979)

Born and raised in Pakistan, Abdus Salam was a mathematically precocious child, getting his Ph.D. by age twenty-five. His major work and contributions were in the mathematical development of what is now called the standard model, in particular, the unification of the weak and electromagnetic forces of nature. He coined the phrase *electroweak theory* and made significant contributions to issues in modern quantum mechanics. Salam predicted, on the basis of his theories, the existence of the weak neutral current (a new form of fundamental interaction) and of W and Z particles (carriers of the weak force), before they were experimentally identified. In many aspects, his work paralleled, but was independent of, the theoretical efforts of Steven Weinberg. Salam left Pakistan in 1957; spent

many years as a professor in Imperial College, London; and later went on to direct the International Center for Theoretical Physics in Trieste, Italy, where he made great strides in improving the connections and opportunities for third-world physicists to participate in world-class research. A pious and devout Muslim, Salam also worked for many years with various UN committees to encourage the advancement of science and technology in developing nations.

Erwin Schrödinger (b. 1887, d. 1961, Nobel Prize 1933)

An Austrian with broad intellectual interests and a distinctly unconventional personal style, Schrödinger is most famous for the equation that bears his name, the fundamental wave equation of quantum mechanics. Schrödinger served in the German army in World War I and submitted two theory papers from the front. As a young physicist, he was asked to give a colloquium on the thesis of de Broglie, and a physicist in the audience commented that he thought this way of talking was rather childish: "To deal with waves, one has to have a wave equation." Schrödinger found that equation in 1926. He is said to have developed the ideas when on holiday with a Viennese girlfriend. (He had many lovers, not always secret from his wife.) Although his work on quantum mechanics followed Heisenberg's, it was in a form that was mathematically more accessible to other physicists. His equation is still the way that quantum mechanics is generally first taught to students today. (He later proved that it is mathematically equivalent to Heisenberg's methods.) Schrödinger's equation was spectacularly successful and opened the way to quantitative (versus qualitative) calculations with the new theory of quantum mechanics. He left Germany in 1933 because of his discomfort with the growing Nazi presence, later returned to Vienna, and ended his career in Dublin. Interestingly, Schrödinger, too, had a hard time with the philosophical implications of the theory he helped develop. He said, "Had I known that we were not going to get rid of this damned quantum jumping, I never would have involved myself in this business."

Steven Weinberg (b. 1933, Nobel Prize 1979)

Steven Weinberg was one of the central figures in the development of the electroweak theory and the standard model. He made the first quantitative prediction of the mass of the W and Z bosons, well before their experimental discovery. His work has spanned the broadest spectrum of issues in particle physics, including strong and weak interactions, neutrino physics, astrophysics, cosmology, and grand unification. He has written several books aimed at the general public and has been a passionate, articulate, and prominent spokesman for support and dissemination of high-energy physics. He is currently a professor at the University of Texas in Austin.

Bibliography

Essential Reading

Barnett, R. M., Muhry, H., Quinn, H. R., *The Charm of Strange Quarks*, New York: Springer-Verlag, 2000. Very readable and up-to-date; a great collection of pictures, anecdotes, and well-organized summaries and explanations. A few symbols and equations, on a level roughly similar to Cindy Schwarz's book (college level but not overly technical; perhaps a slightly higher assumption about the reader's tolerance for "light" math).

Kane, Gordon, *The Particle Garden: Our Universe as Understood by Particle Physicists*, Cambridge: Perseus Publishing, 1996. An excellent text that summarizes many of the central ideas of contemporary particle physics without getting into technicalities. Well written, aimed at a general audience.

Schwarz, Cindy, *A Tour of the Subatomic Zoo*, New York: AIP, 1996. Used as a textbook in an undergraduate course for non-science majors with no physics background, this book is perhaps not quite so entertainingly "readable" as some others, but it is accessible and contains some *slightly* more technical details for the reader who wants to go a little beyond the purely descriptive, qualitative, story level.

't Hooft, Gerard, *In Search of the Ultimate Building Blocks*, Cambridge: Cambridge University Press, 1996. A firsthand account from one of the key theorists who helped create the standard model ('t Hooft won the 1999 Nobel Prize for these contributions). He has tried hard to write a book without math or technical detail and succeeds for the most part; the level is accessible (perhaps on a par with Krauss), although I can't call it easy (especially the last few chapters). But he has a great talent for making analogies with real-world (and, thus, comprehensible) phenomena to explain esoteric ideas.

Weinberg, Steven, *Dreams of a Final Theory*, New York: Vintage Books, 1993. A firsthand account from a key theorist who helped create the standard model (Weinberg won the 1979 Nobel Prize for his contributions). This book is certainly not a textbook (no equations or math whatsoever), nor a typical "summary of particle physics," but it waxes a bit more philosophical about the goals and ideas of modern physics. You may find Weinberg philosophically provocative, but this is a highly literate and pleasurable book.

Recommended Reading

Bodanis, David, *$E=mc^2$*, New York: Walker and Co., 2000. Bodanis is not a physicist, and this book is not about particle physics, but it is a more personal tale of Einstein's famous equation, which of course plays a central role in our understanding of particles and their dynamics. The book is *far* from technical; it's not really even centered on the physics, but rather on the stories, characters, and history leading up to (and following) the development of the equation. The guide for further reading at the end is a good one, with nice descriptions.

Bromley, D. Allan, *A Century of Physics*, Heidelberg: Springer, 2002. This lovely book consists of very short (paragraph-long) discussions of key events and people in the development of physics over the last 100 years, with lots of great pictures. It's a "tour book," beautiful to look at and fun to peruse.

Calle, Carlos, *Superstrings and Other Things: A Guide to Physics*, Bristol: IOP, 2001. Very readable text at a level accessible to a non-science undergraduate. It covers a lot of physics, not just particles. Calle very occasionally uses numbers and equations, at a similar (or slightly higher) level than the Schwartz or Barnett texts, but still nowhere approaching a "physics text" in terms of math requirements. Nice summary boxes and interludes, good selection of illustrations and explanations.

Close, Frank, *The Cosmic Onion*, College Park: American Institute of Physics, 1983. A slightly older book and one of the earlier attempts at "popularizing" particle physics, this book is a bit more terse and technical than the others I've described. It is explicitly intended for "prospective science undergraduates" or "[any] non-scientist prepared to think." It's somewhat tougher going than, for example, Cindy Schwarz's book or Gordon Kane's, but if you want to go a little further into the details, this is an excellent choice.

Close, Frank, Marten, Michael, and Sutton, Christine, *The Particle Explosion*, Oxford: Oxford University Press, 1987. A colorful book, great pictures, nontechnical, complete, lots of history, very descriptive and detailed.

Davies, Paul, *The Last 3 Minutes*, New York: Basic Books, 1996. The title is a takeoff from Steven Weinberg's *The First 3 Minutes*. This book covers a readable selection of topics in modern cosmology (as modern as a decade-old book can be now).

Ferris, Timothy, ed., *The World Treasury of Physics, Astronomy, and Mathematics*, New York: Little, Brown and Company, 1991. A collection of articles by and about scientists. Not all particle physics (even ranges to math and

astronomy, of course!) but very readable and interesting, a nice selection of essays. Not technical at all, but because it is a collection, each article has a different style and level. Some of the short biographies are charming.

Feynman, Richard, see sample list of titles below. If you become interested in Feynman (it's nearly impossible not to!), I recommend just about anything written by Feynman himself. For entertainment, you can't beat his "autobiographies." Start with *Surely You're Joking, Mr. Feynman: Adventures of a Curious Character*, 1985 (Norton and Co.), followed by *What Do You Care What Other People Think? Further Adventures of a Curious Character*, 1988. For some real physics from the master, I recommend *6 Easy Pieces*, Helix Books, 1994, a compilation of six lectures about topics in modern physics Feynman gave to his freshman students at CalTech. These are truly brilliant. Another similar text, this time about more classical questions in physics, is *The Character of Physical Law*, MIT Press (1985). Feynman also wrote *QED: The Strange Theory of Light and Matter*, Princeton University Press (1985), in which he attempts to explain QED to non-experts. An interesting book, but I believe it's still a little hard. I'm not sure if Feynman completely succeeded with his goal on this one, but it's definitely worth a look if you really want to dive deeper.

Franklin, Allan, *Are There Really Neutrinos: An Evidential History*, New York: Perseus Books, 2003. This book is different from most in this list, being written by a historian and philosopher of physics (also a particle physicist). It focuses on the history of neutrinos, addressing the fundamental question: Why do we believe in the reality of particles like the neutrino? Could the neutrino be a social construct rather than something real? An interesting perspective. Mild warning: The book is technical in many places, definitely aimed above the "novice general public" in my opinion.

Fraser, Gordon, *The Quark Machines: How Europe Fought the Particle Physics Wars*, Bristol: Institute of Physics Publishing, 1997 (paperback). Nontechnical summary of more recent developments, with an unusually international perspective, a good deal of discussion of the people involved, good list of references for further reading.

Gamow, George, *Mr. Tompkins in Paperback*, Cambridge: Cambridge University Press, 1993. A whimsical book, very amusing, although a bit dated. Mr. Tompkins is an "interested layperson" who attends lectures on modern physics for the public, but alas, he inevitably falls asleep partway into the lecture. This book describes his ensuing dreams, in which the laws of physics being discussed are "visualized" in some dramatic way. For example, when Mr. Tompkins falls asleep while learning about relativity, in his dream, the speed of light is only about 25 miles/hour; thus, relativity effects become "visible" as he walks around town or gets in his car. In the lecture about quantum mechanics, Planck's constant (which tells the strength of quantum effects) is huge, and billiard balls on Tompkins's pool table suddenly "fuzz out," then tunnel off the table. Very creative way of presenting physics, although the topics covered are not exactly the most "modern" particle physics.

Glashow, Sheldon, *Interactions: A Journey through the Mind of a Particle Physicist and the Matter of This World*, New York: Warner, 1988, and *The Charm of Physics*, College Park: AIP Press, 1991. Two books by a Nobel Prize winner, both light in style, entertaining, filled with stories, from a somewhat personal perspective. Both books also contain a great deal of particle physics. Recommended.

Gleick, James, *Genius: The Life and Science of Richard Feynman*, New York: Pantheon Books, 1992. Not about the physics, but a biography of Richard Feynman, well written, a good glimpse at this remarkable character.

Greene, Brian, *The Elegant Universe*, New York: Vintage Books, 2000. Greene has tried to meet a great challenge—to write a "popular" book about the most abstract and mathematically complex physical theory of them all, string theory. He does a great job, but it's not always the easiest going. I suspect that the casual reader will often be left a little dizzy. Still, Greene manages to "return to reality" enough to allow you to continue reading and continue getting a lot out of the book right up to the end. This is hard stuff, and Greene does an amazing job of presenting it without getting technical.

Hawking, Stephen, *A Brief History of Time* and *The Universe in a Nutshell*, New York: Bantam 2001. Stephen Hawking is one of the most celebrated and well-known contemporary physicists. His books (sometimes considered "coffee-table books," in the sense that some people buy them but don't actually read them) are comprehensive, up-to-date, and full of wonderful ideas about modern physics. However, I often find that when I get to material about which I'm not an expert, Hawking can lose me; I imagine this could be a problem throughout for the non-physicist reader. I also find that Professor Hawking has some strong ideas that sometimes reach well beyond particle physics, to the realm of philosophy and interpretation, which the reader should be aware of. Interesting books nonetheless.

Kevles, Daniel J., *The Physicists*, Cambridge: Harvard University Press 1995. History of particle physics, more focused on the earlier years. A little dry and dense, but lots of interesting details and anecdotes. I found the introduction/preface on the rise and fall of the SSC especially interesting.

Krauss, Lawrence M., *Fear of Physics*, New York: Basic Books, 1993. Delightful book. Not about particle physics per se (although that's clearly his focus). More a book about how physicists think, how they approach problems. As the book progresses and Krauss gets more into the details and explanations of modern particle physics ideas, the reader may become a little lost because of the completely nontechnical approach (all examples are analogies or simple pictures), but it's a creative and insightful book. Definitely recommended. I just loved the opening chapters.

Landsberg, Peter T., *Seeking Ultimates: An Intuitive Guide to Physics*, Bristol: IOP Publishing, 2000. A popular-style account of many of the fundamental ideas of physics, not limited to particle physics. Some personal philosophy is also mixed in with the book; the author believes deeply that physics is, and always will be, incomplete, but that it is the journey that is most important. Quite readable and a little broader in scope than many of the other books I have included.

Lederman, Leon, *The God Particle*, Boston: Houghton Mifflin, 1993. Whimsical, with a light style and lots of bad puns, a Nobel Prize-winning experimentalist's take on the significance, content, and meaning of particle physics. This is not a book filled with technical explanations or details; it's more a collection of stories and insights, with lots of history and fascinating introduction. Very entertaining reading and still up-to-date. (I find his curious renaming of the Higgs to be completely inappropriate and somewhat annoying, but then, he's the one with the Nobel Prize.)

Leighton, Ralph, *Tuva or Bust*, New York: W.W. Norton and Co., 1991. A less scholarly but more personal work about Richard Feynman. A breezy and delightful story of Feynman as a friend and human being.

Pais, Abraham, *Inward Bound*, Oxford: Oxford University Press, 1988. A slightly more technical book, aimed at scientists (though not necessarily physicists). It's a little dense, very comprehensive, but quite readable if you are comfortable with a few equations and a little mathematical reasoning.

Park, Robert, *Voodoo Science*, Oxford: Oxford University Press, 2000. This book has nothing directly to do with particle physics, but it's a fascinating story of "the road from foolishness to fraud." It's about "bad science," with thoughts on how to distinguish real science from the marginal. The author, Robert Park, is strongly opinionated; if you disagree with him, you may find his strength of conviction challenging, but I think it's a good representation of where most working physicists stand. Great reading, very interesting, entertaining, and thought provoking.

Riordin, Michael, *The Hunting of the Quark*, New York: Simon and Schuster, 1987. A historical narrative focusing on the 1960s–1970s, with many anecdotes and stories about the people and events, as well as the physical ideas. No math but occasional overuse of jargon. The chapters on the November Revolution are among the best of the lot, though.

Taubes, Gary, *Nobel Dreams: Power, Deceit, and the Ultimate Experiment*, New York: Random House, 1987. The "human side" of particle physics, with all the hubris, ego, deceit, confusion, and passion exposed. Much more entertaining reading than most of the other references I've provided, although by its nature, less physics and more soap opera!

Wearth, S., and Phillips, M., eds., *History of Physics: Readings from Physics Today*, Heidelberg: Springer, 1987. A variety of articles, although nothing really state of the art. I especially enjoy "The Birth of Elementary Particle Physics" (Laurie Brown and Lillian Hoddeson, from *Physics Today*, April 1982.)

Weinberg, Steven, *The First 3 Minutes*, New York: Basic Books, 1993. An excellent introduction to the Big Bang and the origin of our universe. Although there have been some important theoretical developments since this book was written, it is still relevant. The level of the book is above the "purely popular," a bit more on the level of an undergraduate text (but suitable for a non-physics major).

Wilczek, Frank, and Devine, Betsy, *Longing for the Harmonies*, New York: Norton, 1987. Although the book is fifteen years old, it is still quite relevant, because the authors do not try to teach the details of modern physics, but rather, to give a taste of the type of aesthetic and intellectual issues involved. They focus on the "musical metaphors" of science. The authors believe that modern physics is not commonsense, but neither is it mystical or incomprehensible. This book is chock full of gems, lots of wonderful insights about the world that help clarify what modern physics is about. I recommend it highly.

Web Sites

http://www.nobel.se/physics/laureates/index.html. The Nobel Prize page for physics, with detailed links if you're curious to follow up on any of the people or ideas.

http://press.web.cern.ch/pdg/particleadventure/other/suggestedreading.html. An excellent collection of additional readings from CERN, the European center for particle physics. Very comprehensive.

http://www.pparc.ac.uk/Ed/ppres_books.asp?Pv=1. PPARC is a particle physics site from the United Kingdom. This site offers a collection of links with many book suggestions (with summaries and "level descriptions"). A useful source for finding further readings.

http://www.fnal.gov. Fermilab's central Web site; this is the premier particle physics experimental facility in the United States. The facility has a solid public outreach program, and its Web site is well organized and interesting, with lots of material aimed at the non-physicist. If you are interested in getting some K–12 students involved in learning about particle physics, the link http://quarknet.fnal.gov is a great resource.

http://www.slac.stanford.edu. SLAC (Stanford Linear Accelerator Center) is the "other" premier U.S. particle physics experimental facility. This site has a great deal of information for the public, and the www.slac.stanford.edu/history/ link is a nice one.

http://particleadventure.org/. Comprehensive and educational site, highly recommended. Created by the Particle Data Group. The site is aimed at, perhaps, the high school level, but I find it informative and educational for any interested readers. Another related link is http://www.cpepweb.org/ particles.html.

http://public.web.cern.ch/Public/. This is the Web site of CERN (the premier European particle physics facility) aimed at the public. Lots of easily readable information about particle physics here.

http://www.sno.phy.queensu.ca/. The SNO collaboration's Web site, a good place to find its latest news and summaries of other experimental efforts.

http://pdg.lbl.gov. The central repository summarizing all standard model information, compiled by the Particle Data Group of Berkeley.

http://cpepweb.org. The "wall chart" of particle physics. This is from the Particle Data Group. The links to the group's more technical Web pages contain an incredible summary of all the detailed quantitative knowledge we have accumulated regarding all fundamental particles and the laws of physics.

http://dbserv.ihep.su/compas/contents.html. A chronology of particle physics ideas, with links to original papers. Very comprehensive for those interested in historical aspects.

http://www.aps.org/resources/particle.html. American Physical Society page with many links (and descriptions of those links), heading to a variety of resources appropriate for everyone from students in grades K–12 to interested members of the public to working physicists.

http://www.hep.ucl.ac.uk/~djm/higgsa.html. In 1993, the then U.K. Science Minister, William Waldegrave, issued a challenge to physicists to answer the questions "What is the Higgs boson, and why do we want to find it?" on one side of a single sheet of paper. Here is David J. Miller's prize-winning "qualitative layperson's explanation." Other replies can be found at http://hepwww.ph.qmw.ac.uk/epp/higgs.html.

http://www.sns.ias.edu/~jnb/. John Bahcall's Web site, with a focus on solar neutrinos (check the link on the left for "popular accounts").

http://scienceworld.wolfram.com/physics/. Eric Weisstein's "World of Physics," with short biographies of just about every physicist I've ever heard of. Nice historical/biographical reference, although rather brief in most cases.

http://dept.physics.upenn.edu/~erler/electroweak/index.html. An up-to-date summary of quite technical information about the status of the standard model, maintained by Jens Erler and Paul Langacker at the University of Pennsylvania Some of it may be readable, but for the most part, it is designed for particle physicists.

http://www.aip.org/history. Excellent site, very readable, with a small (but growing) collection of historical hypertexts of some key physicists and physics topics.

http://www.powersof10.com/. Not exactly particle physics, but a wonderful site to help think about the world at different distance/size scales.